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Sequential Nitrification-Denitrification in a Plug Flow Activated Sludge System

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16. ABSTRACT The use of the carbon sources present in municipal wastewater to provide the energy required for nitrification-denitrification was evaluated on a pilot plant scale in a simulated plug flow reactor. Most of this report is devoted to the results from operation of a nine-pass activated sludge system receiving primary effluent. The first two passes and the last pass were aerated whereas the remaining passes were mechanically mixed. Nitrification occured in the aerated passes and denitrification in the others. By maintaining a sufficiently low process loading, nearly all of the incoming ammonia was oxidized in the first two passes with most of the nitrate subsequently denitrified in the next six passes. Residual NH_4^+-N levels of 0.1 mg/l and $(NO_2^- + NO_3^-)$-N levels of 1.0 mg/l were obtained with both steady state and diurnal flow. $FeCl_3$ addition during a portion of the study increased the P removal to approximately 90% with no discernible impact on the nitrification-denitrification performance.

Nitrification and denitrification kinetic rates measured during laboratory studies were found to correlate well with actual process rates. These rates were obtained under varying conditions of temperature, available COD, length of initial aeration period, etc.

If chemical addition is to be used for the control of filamentous organisms without impairing the autotrophic nitrifying organisms, chlorine appeared to offer a much greater potential for success than did H_2O_2.

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SEQUENTIAL NITRIFICATION-DENITRIFICATION IN A PLUG FLOW ACTIVATED SLUDGE SYSTEM

by

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FOREWORD

The Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimony to the deterioration of our natural environment. The complexity of that environment and the interplay between its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution and it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems for the prevention, treatment, and management of wastewater and solid and hazardous waste pollutant discharges from municipal and community sources, for the preservation and treatment of public drinking water supplies, and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research; a most vital communications link between the researcher and the user community.

The study summarized in this report demonstrates that the carbon sources naturally present in municipal wastewater can be effectively utilized to provide the energy required for the dissimilatory reduction of NO_3^--N in a process using a single nitrification-denitrification cycle.

Francis T. Mayo, Director
Municipal Environmental Research
Laboratory

ABSTRACT

The use of the carbon sources present in municipal wastewater to provide the energy required for nitrification-denitrification was evaluated on a pilot plant scale in a simulated plug flow reactor. The majority of this report is devoted to the results from operation of a nine-pass activated sludge system. Results from the operation of a four-pass and an eight-pass reactor are also briefly summarized. The nine-pass reactor received primary effluent from the District of Columbia wastewater treatment plant. The first two passes and the last pass were aerated whereas the remaining passes were mechanically mixed. Nitrification could occur in the aerated passes and denitrification could occur in the others.

The nine-pass reactor was operated for over a year with nitrification-denitrification routinely achieved. By maintaining a sufficiently low process loading, nearly all of the incoming NH_4^+-N could be oxidized in the first two passes with most of the $(NO_2^- + NO_3^-)$-N subsequently denitrified in the next six passes. Residual NH_4^+-N levels of 0.1 mg/l and $(NO_2^- + NO_3^-)$-N levels of 1.0 mg/l were obtained with both steady state and a diurnal flow cycle. When the loading to the first two passes was sufficiently high to prevent all NH_4^+-N from being oxidized prior to exiting the second pass, there was a corresponding rise in the effluent nitrogen residuals. $FeCl_3$ addition to the ninth pass of the system during a portion of the study increased the P removal to approximately 90% with no discernible impact on the nitrification-denitrification performance.

Downflow dual media filters were fed clarified effluent during the period of $FeCl_3$ addition. Filtered effluent quality was as follows: BOD=1.5 mg/l; SS=2 mg/l; P=0.25 mg/l; NH_4^+-N=0.2 mg/l; and $(NO_2^- + NO_3^-)$-N=0.9 mg/l. The filter with the larger media produced an effluent quality identical to that attained with smaller media but run lengths were 50% longer.

Nitrification and denitrification rates measured during laboratory kinetic studies were found to correlate well with actual process performance. The length of the initial aeration period exerted a marked impact on the subsequent denitrification rates. When the aeration period was not excessive, there was no apparent advantage in utilizing a flow-splitting approach with part of the primary effluent bypassed directly to denitrification. Accelerated denitrification rates were obtained in laboratory studies with added KNO_3 during the period of soluble COD removal from primary effluent. However, other studies indicated that the soluble COD was normally removed under aerobic conditions in less time than required for complete NH_4^+-N oxidation.

The use of chemical addition for the control of filamentous organisms was studied and chlorine appeared to have fewer adverse effects on the autotrophic nitrifying organisms than did H_2O_2.

This report was submitted in fulfillment of Contract No. 68-03-0349 by the Government of the District of Columbia under the sponsorship of the U.S. Environmental Protection Agency. This report covers the period September, 1974 to July, 1976, and work was completed as of January, 1977.

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The efforts of all of the mechanics, technicians, crew chiefs, operators, and laboratory personnel are gratefully acknowledged.

SECTION 1

INTRODUCTION

Nitrogen removal from wastewater can be accomplished by a number of alternative biological and/or physical-chemical treatment sequences. The choice of the most effective process or combination of process sequences can, of course, only result from a thorough engineering evaluation of the various options based on the characteristics of the water to be treated in conjunction with the degree and reliability of treatment required. Options available to satisfy nitrogen removal criteria have been summarized in considerable length in a process design manual for nitrogen control (1).

Biological removal of nitrogenous materials in activated sludge systems beyond that obtained as a result of cellular synthesis can be achieved by oxidation of the NH_4^+ to NO_3^--N followed by the dissimilatory reduction of the nitrate to nitrogen gas (also NO or N_2O). In the days prior to emphasis on nutrients in discharge waters, this phenomenon was often mentioned in the context of a nuisance associated with rising sludge in the secondary clarifiers. In recent years, however, the dissimilatory reduction of NO_3^--N has been deliberately exploited as a viable methodology for nitrogen removal. In most biological denitrification systems an external carbon source such as methanol has been added to accomplish dissimilatory nitrate reduction. Although this technique is quite effective and easy to control, the cost of the external carbon source can be considerable and extra biological sludge is produced. In an effort to reduce costs, attention has recently been turned to systems which use internal carbon sources (the organics already in the waste and endogenous metabolism) for biological denitrification.

The use of internal carbon sources and/or endogenous respiration to achieve dissimilatory NO_3^- reduction is certainly not a new concept. A number of investigators have examined alternative flow processes/schemes to achieve this objective. Ludzack and Ettinger (2) reported on a sequence to accomplish internal denitrification in 1962. A flow sequence very similar to that utilized in the present investigation was reported by Wuhrmann in 1964 (3). A summary of the available literature on biological denitrification was presented by Christensen and Harremoes (4) and updated through early 1975 by these authors (5) at the August 1975 IAWPR specialized conference. That conference was devoted to nitrogen as a water pollutant, and the conference proceedings (6) contain an excellent compilation of much of the current work on single stage systems for nitrification-denitrification. The literature reviews (4,5) conference proceedings (6) and EPA Design Manual (1) provide considerable information and literature references on biological approaches to nitrification-denitrification and there is little point in repeating this

information here. However, a very brief summary of some of the more fundamental aspects and considerations will be presented in Section 4 for those who may not be familiar with the basic details.

In the study reported on here, a pilot plant evaluation of the efficacy of the system originally proposed by Wuhrmann was conducted. In this system a plug-flow activated sludge reactor is operated with three zones in series. In the first, oxidation of exogenous carbon and nitrogen takes place; in the second reduction of nitrate with oxidation of endogenous or adsorbed carbon takes place; in the third oxidation of residual carbon and nitrogen is accomplished.

SECTION 2

CONCLUSIONS

1. A multipass reactor can be reliable operated to allow the incoming ammonia to be oxidized to nitrate at the head of the reactor. When the mixed liquor is then sent to the anoxic sections of the reactor, denitrification will occur. A terminally aerated pass/section in the reactor is desirable to degasify the mixed liquor prior to clarification, and to oxidize any residual ammonia to nitrate.

2. Use of a nine-pass reactor to provide a single nitrification-denitrification cycle followed by a final aeration step produced effluent NH_4^+-N residuals of 0.1 mg/l and (NO_2^- + NO_3^-)-N concentrations of $\sim$ 1.0 mg/l when treating District of Columbia primary effluent. These results were achieved with both steady and diurnal flow patterns.

3. Nitrification and denitrification kinetic rates measured in laboratory studies were found to correlate well with actual process performance. Laboratory kinetic studies also indicated that bypassing a portion of the primary effluent directly to denitrification was not needed to insure good denitrification, provided the length of the initial aeration period was not excessive. Aeration beyond that needed to achieve nitrification resulted in a noticeable decline in the subsequent denitrification rate.

4. $FeCl_3$ addition directly to the mixed liquor in the last reactor pass increased phosphorus removals to near 90%. No detrimental impact on the nitrification-denitrification performance was observed.

5. When parallel downflow dual-media filters with differing filtering media were fed clarified effluent, they produced filtered effluents of identical quality. However the increased run lengths achieved with the larger media (64 cm of 2.0 mm ES anthracite and 38 cm of 0.9 mm ES silica sand) clearly indicated that this filter was superior to the one with smaller media (64 cm of 1.3 mm ES anthracite and 38 cm of 0.65 mm ES silica sand).

6. Low activated sludge settling velocities and high SVI's were encountered with the single stage system used in this study. These are typical of results with most single stage systems.

7. If chemical addition is to be used for the control of heterotrophic nuisance growths without impacting the nitrifying organisms, chlorine appears to offer a much greater potential for success than does H_2O_2.

SECTION 3

RECOMMENDATIONS

The previous results of Wuhrmann (3), Christensen et al. (7), and the results from the present study clearly indicate that a single nitrification-denitrification approach can reliably produce high nitrogen removals. Similarly a number of other approaches involving internal carbon sources have also been shown to be effective. A major difficulty is attempting to extrapolate the particular flow/concentration/temperature characteristics of a given wastewater into the most effective process configuration for that particular set of circumstances. Further careful experimentation is needed to better define the denitrification rates as a function of all the variables involved. If this could be done, it may be possible to reduce the 10-fold range of kinetic values considered "typical" of single state systems into better design procedures for the amount of denitrification capacity needed.

One difficulty with this system was the need for very large clarifiers because the activated sludge has poor sedimentation properties. During periods when iron was added to precipitate phosphorus, significant improvement in clarification was achieved. The use of other weighing agents to improve clarification in these types of systems should be evaluated.

SECTION 4

BACKGROUND CONSIDERATIONS

Oxidation of ammonia to nitrite is accomplished by the chemoautotrophic Nitrosomonas organisms. The subsequent conversion of the nitrite to nitrate is the result of the chemoautotrophic Nitrobacter species. Although a number of heterotrophic bacteria can also oxidize inorganic nitrogen, there is no indication that they play a significant role in wastewater treatment (8). The combined result of the nitrogen transformations brought about by Nitrosomonas and Nitrobacter can be summarized as follows:

$$NH_4^+ + 2\ O_2 \longrightarrow NO_3^- + 2\ H^+ + H_2O$$

The stoichiometric oxygen requirement is 4.57 mg of O_2 per mg of NH_4^+-N oxidized. Each mg of NO_3^--N formed results in the corresponding destruction of 7.14 mg of alkalinity as $CaCO_3$.

In the absence of dissolved oxygen, a number of facultative heterotrophic bacteria commonly present in wastewater treatment systems are able to utilize NO_3^- as a terminal electron acceptor with the resultant formation of nitrogen gas (also NO or N_2O). The electron donor (carbonaceous energy source) can either be added as an external carbon source such as methanol or one can utilize a system in which the carbon source naturally present in the wastewater also serves in the dissimilatory nitrogen reduction process. The stoichiometric quantity of alkalinity produced per mg of NO_3^--N reduced to N_2 gas is 3.57 mg as $CaCO_3$. Hence denitrification partially offsets the alkalinity loss caused by nitrification.

In municipal and domestic wastewater, the nitrogen entering the treatment plant is predominantly organic nitrogen and ammonia nitrogen. NO_3^- may be present in low concentrations in some cases. However in most instances, such as at the District of Columbia Wastewater Treatment Plant where this study was conducted, the nitrate initially present has already been reduced by the time the wastewater arrives at the treatment plant. Hence the normal situation is that the nitrogen must first be oxidized to NO_3^- before it can be reduced to N_2 gas. It should be noted that there are certain industrial waste situations where large quantities of NO_3^- and degradable organic material may be initially present in the wastewater and in this case the dissimilatory reduction of the NO_3^- to nitrogen gas may be accomplished in an initial anoxic biological treatment step (9). Alternatively in a municipal wastewater plant with aerobic sludge digestion there is the likelihood of

encountering a waste stream high in NO_3^- and this also may present an option for the dissimilatory reduction of this material with an anoxic treatment step should this be desired.

General process alternatives available to achieve nitrification-denitrification using internal carbon sources are shown in Figure 1. In the first process scheme both carbonaceous oxidation and nitrification occur in the first basin with endogenous denitrification in the second basin. This general flow sequence may or may not include a terminally aerated chamber but some aeration time should be provided to at least degasify the mixed liquor and improve the sludge settling characteristics. A major advantage of this process is its' inherent simplicity and ease of operation. An additional option with this general approach is to bypass a portion of the raw or primary sewage directly to the denitrification chamber to accelerate the rate of denitrification. This, of course, results in the introduction of unoxidized organic compounds and ammonia nitrogen into the process. These reduced nitrogen forms cannot be removed in the denitrification reactor. The use of a terminally aerated chamber can allow for the conversion of this residual nitrogen to nitrate nitrogen and insure the oxidation of any remaining unmetabolized carbonaceous materials introduced with the bypassed wastewater.

In the second general process scheme shown in Figure 1, mixed liquor in which the NH_4^+-N has been oxidized to NO_3^--N is recycled back and mixed with the incoming sewage in the lead denitrification reactor. This flow sequence insures a ready supply of external carbon to accelerate the denitrification rate in the first reactor but requires recycling of the second basin mixed liquor at a rate which may be several times that of the incoming flow. The second basin is operated to provide for nitrification and associated carbonaceous oxidation. This basin can be followed by additional denitrification and nitrification basins to further reduce the nitrate level from the second basin. In this case, reliance is placed on endogenous denitrification for NO_3^- reduction in the second denitrification basin.

In the third general process sequence carbonaceous oxidation, nitrification and denitrification all occur in "one" basin. This an be accomplished by careful positioning of surface aerators to provide aerobic and anaerobic zones; by alternating the flow and/or air supply to different basin sections; or by use of the Pasveer system, the Carrousel plant or the Orbal plant to provide alternating aerobic and anaerobic zones.

It can be seen that a number of process options are available to achieve denitrification without reliance on external carbon sources such as methanol. All of the process schemes discussed above have been employed in actual practice and the literature reviews by Christensen and Harremoes (4,5) and the 1975 IAWPR specialized conference proceedings (6) serve as a ready guide to this information.

There are a few generalizations which can be made concerning all three of the process schemes presented in Figure 1. No matter what system is utilized it is necessary to provide a sufficiently long solids retention time (SRT) to insure the growth of nitrifying organisms, a sufficient aerated

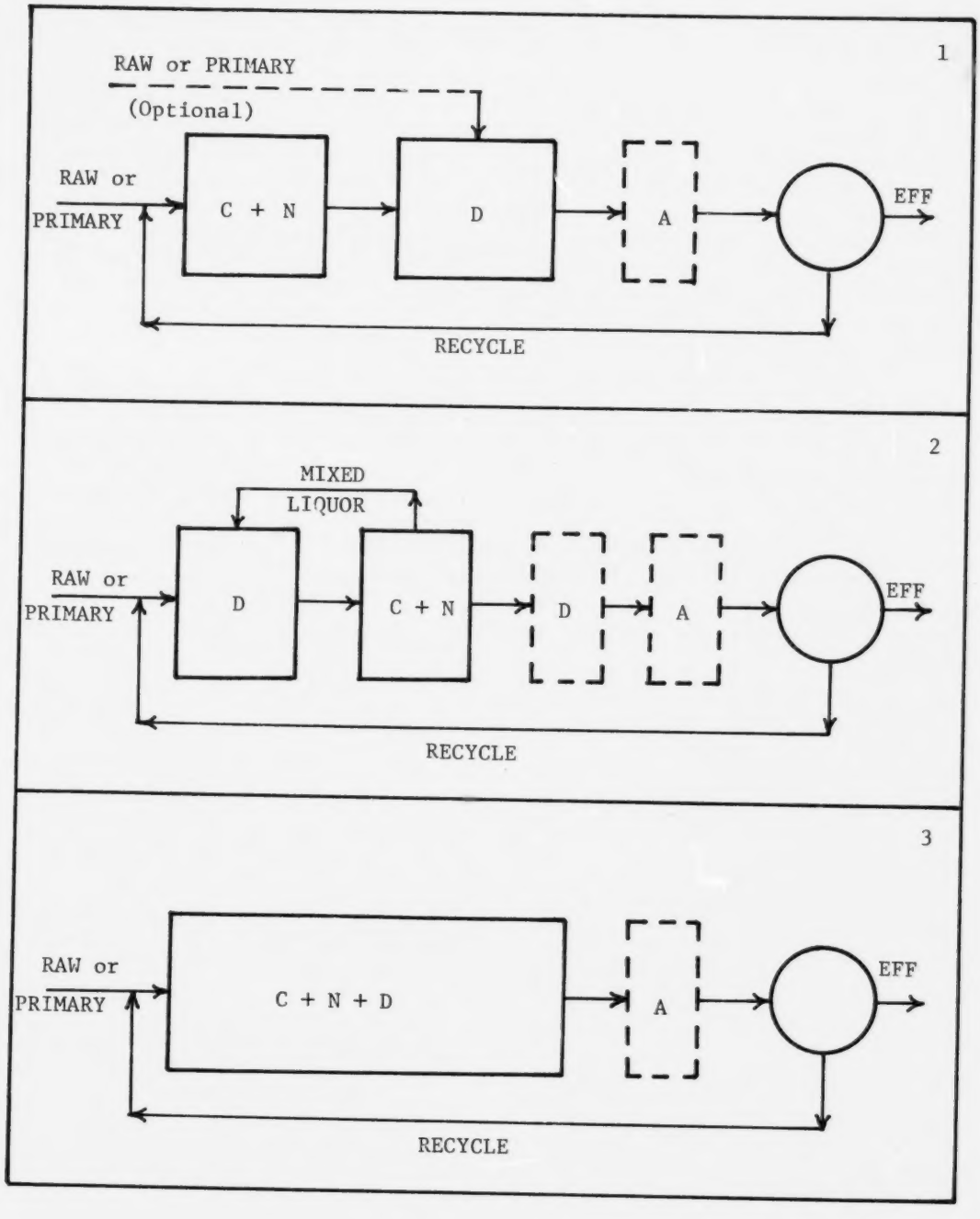

Figure 1. Three general flow schemes for achieving nitrification-denitrification using internal carbon sources.

basin volume at a dissolved oxygen (D.O) level adequate for nitrification to occur, and an anaerobic basin or anaerobic section for dissimilatory nitrate reduction. Obviously no matter what flow scheme is considered, the designer must attempt to reconcile the divarications inherent in combining both nitrification and denitrification into one process. Long aeration times and high D.O. levels promote nitrification at the expense of the carbon source available for denitrification. Alternatively, the anaerobic conditions necessary for denitrification provide an environment in which the nitrifying organisms cannot grow. Also as conditions are changed to allow for more and more unmetabolized carbon source to be present to accelerate the denitrification rate, there will be a corresponding increase in the concentration of NH_4^+-N which must first be oxidized to NO_3^- prior to it's availability for dissimilatory reduction. As noted by Christensen et al. (7), a certain amount of brinksmanship is needed in order to achieve high nitrogen removal.

Because of the generally favorable economic position of nitrification and denitrification for nitrogen removal compared to other available physical-chemical processes, the use of these biological processes would normally be considered as part of any design where nitrogen removal is required. In some cases toxicity considerations or the need to provide nitrogen removal only at certain selected times of the year may provide sufficient constraints to discount the usefulness of biological processes. Where this is not the case, a single stage system has the potential of playing an integral part in the final process design as either the basic treatment process or as a system component in a more complex nitrogen control strategy.

SECTION 5

EXPERIMENTAL SYSTEMS AND PROCEDURES

The experimental systems selected for evaluation in the present study were adaptations of the first general flow scheme presented in Figure 1. The actual process configuration that was investigated throughout most of the study is shown in Figure 2. The reactor consisted of nine compartments connected in series. The first eight passes were constructed by making minor modifications to two side-by-side oxygen activated sludge pilot system reactors. The first eight passes were of equal size with a total liquid volume of 61.3m^3 (16,200 gal). The ninth pass was constructed from other tankage and held a liquid volume of 7.04 m^3 (1860 gal). The first, second, and ninth passes were aerated by discharging compressed air into 2.5 cm (1 in) PVC perforated pipe sections placed at the bottom of each reactor pass. The air flow rate to each pass was controlled manually with a ball valve in each air line. Mechanical energy for mixing passes 3 thru 8 was supplied by individual Philadelphia Gear mixers located above each pass and turning a long mixer shaft with a 30 cm (12 in) impeller. Each of the nine passes was open to the atmosphere.

Flow from the ninth pass went through a splitter box and on to two center feed clarifiers each with a cross-sectional area of 7.2 m^2 (78 ft^2) based on clarifier diameter. Underflow solids were returned to the head of the process with variable speed Moyno pumps. Sludge wasting was controlled by manually diverting each recycle stream to a calibrated drum once or twice per day depending upon the waste volume desired.

Influent flow consisted of primary effluent pumped with a centrifugal pump through a magnetic flow meter to the first reactor pass. During the study with an imposed diurnal flow, a Data-Trak programmer was used in conjunction with a pneumatically controlled valve to provide the desired flow pattern. Flow meter accuracy was checked once per week by diverting the metered flow to a calibrated drum. The actual flow was manually recorded once per day from a flow totalizer connected to the magnetic flow meter and the results from the weekly flow meter checks were used to correct the recorded values when necessary.

During a portion of the study, $FeCl_3$ was added to the ninth pass of the reactor by means of a simple peristaltic pump. Since this portion of the study was conducted with a steady influent flow, a constant chemical feed rate was maintained. Also during the period of $FeCl_3$ addition, a portion of the effluent from one of the clarifiers was pumped to two gravity downflow filters as shown in Figure 3.

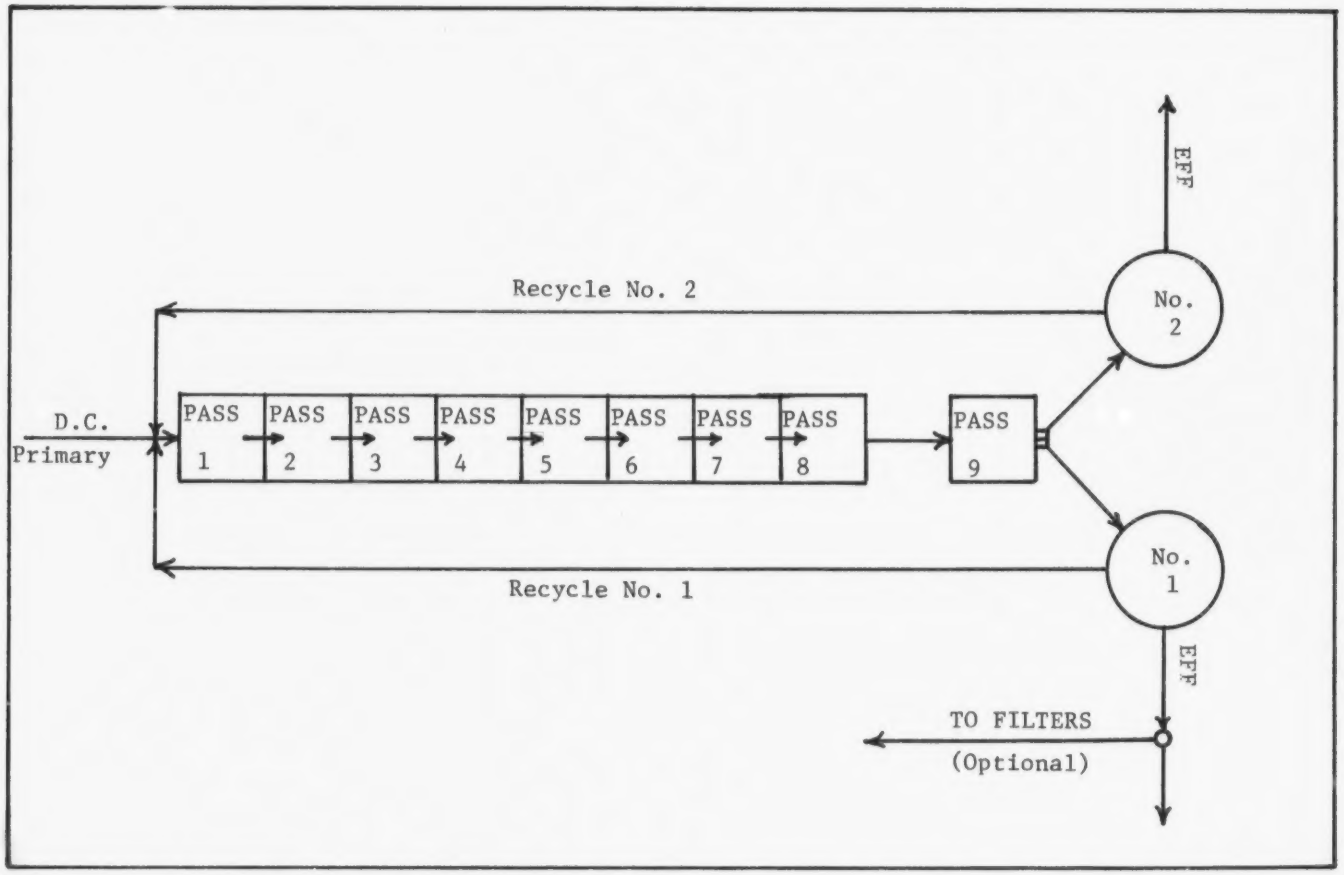

Figure 2. Schematic diagram of the nine-pass reactor used in the present investigation.

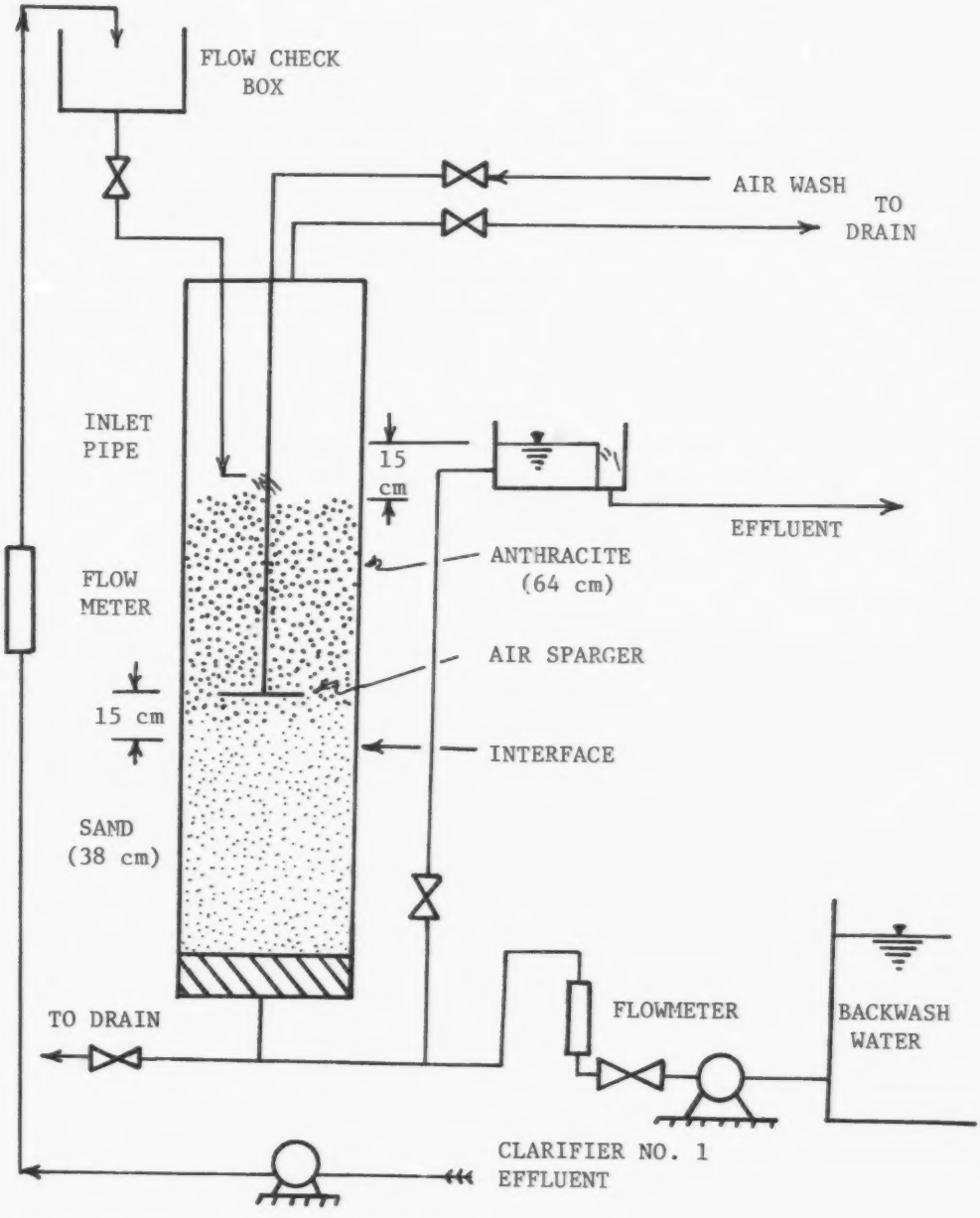

Figure 3. Schematic diagram of downflow dual media filter.

The filters were constructed of 35.6 cm (14 in) diameter clear plexiglass columns approximately 2.4 m (8 ft) in length, each having a lateral surface area of 0.1 m^2 (1 ft^2). Taps were provided at 7.6 cm (3 in) intervals to monitor the differential pressure across the media. A 0.14 m^3/min (5 scfm) air wash system was installed for use during backwash. For backwashing of the filters, tap water was pumped from a holding tank upward through the media and discharged to drain. The support media consisted of approximately 15 cm (6 in) of 1.3 cm (0.5 in) diameter stone, above which was placed 10 cm (4 in) of 0.3 cm (.125 in) diameter garnet to prevent the overlying sand from penetrating the support media. The filter media consisted of approximately 38 cm (15 in) of sand under 64 cm (25 in) of anthracite coal.

As the differential pressure increased across the filter media, the height of the water increased in the column to maintain constant flow. A maximum of 3 m (10 ft) of total head was available, although backwash operations were initiated when the head exceeded 2.5 m (8.3 ft). The backwash sequence was as follows:

(1) 1 min. of air scour at 1.5 $m^3/min/m^2$ (5 $scfm/ft^2$).
(2) partial filter drainage to top of media.
(3) 1 min. air scour with 2 min. low flow, 0.4 $m^3/min/m^2$ (10 gpm/ft^2) backwash.
(4) 10 min. of high flow, 1.2 $m^3/min/m^2$ (30 gpm/ft^2) backwash.

Throughout the study samples of mixed liquor from the last reactor pass were periodically removed and settling tests were run in 2.3 m x 0.15 m (7.5 ft x 6 inches) diameter stirred columns. The stirring mechanism consisted of two 0.64 cm (1/4 inch) diameter rods which extended the length of the column and rotated around the vertical axis at a rate of 15 rph. Settling rates in which the recycle solids were mixed in varying proportions with the clarified process effluent were also determined on two occasions.

The process was operated on a 24-hour a day, 7-day a week schedule. The only interruptions in the normal operating sequence resulted from mechanical malfunctions and these were normally of short duration. No process data are presented in this paper from any period with excessive mechanical malfunctions.

Grab samples of reactor influent and both clarified effluents (and filter influent and effluents during their operation) were manually taken every four hours, and grab samples of mixed liquor and recycle solids were manually obtained every eight hours for the laboratory analyses described below. The grab samples were composited over a 24-hour period on Tuesday, Wednesday and Thursday; samples collected on Friday-Saturday and on Sunday-Monday were composited over the 48-hour period. The single exception to this was that the samples for BOD_5 measurement were always 24-hour composites and the analysis was always started within a few hours (4-10 hours) after the last sample for each 24-hour composite had been collected. All samples were refrigerated at 2°C prior to analysis. In addition, all samples except those taken for BOD_5 or suspended solids analysis were preserved with one

drop of H_2SO_4 per 30 ml of sample while they were being held in storage. All laboratory analyses (except BOD_5) were performed on a Monday through Friday schedule.

The following analyses were performed in the District of Columbia Pilot Plant laboratories according to the procedures specified in Standard Methods (10): suspended solids, volatile suspended solids, BOD_5, COD and TKN. Also BOD_5 analyses of effluent samples were performed with nitrate production inhibited by the addition of 0.5 mg/l of allylthiourea (11). The procedures specified in the EPA Manual (12) were used for the determination of (NO_2^- + NO_3^-)-N with a Technicon autoanalyzer. NH_4^+-N was measured by a Technicon analyzer using modifications of the methods of Scheiner (13) or Kamphake (14). The method of Gales et al. (15) was used for the determination of total phosphorus. (NO_2^- + NO_3^-)-N and NH_4^+-N measurements during laboratory kinetic studies were both made with Technicon analyzers following the procedures in the EPA Manual (12).

In addition to collecting grab samples and compositing them for subsequent laboratory analysis, the operating personnel also: (a) checked the mixed liquor dissolved oxygen levels in the aerated passes every four hours with a portable Delta Scientific field probe and adjusted the air flow rates as needed to attempt to maintain a D.O. concentration of 2-4 mg/l in the first, second and ninth passes; (b) obtained selected solids samples for 30-minute sludge volume determinations in one-liter cylinders; (c) measured temperature, pH and alkalinity of selected samples; (d) measured the depths of the sludge blankets in the clarifiers with a photoelectric cell; (e) checked the $FeCl_3$ feed rate during this portion of the study; and (f) recorded the pressure drop across the filters and backwashed when necessary.

On numerous occasions batch kinetic studies to determine nitrification and/or denitrification kinetic rates were undertaken in the laboratory with process solids withdrawn from the recycle stream of the nitrification-denitrification system. Although the laboratory studies employed varied methodologies, a few generalizations can be made. A water bath was always used to insure that the temperature of the culture during the kinetic analysis remained the same as that which existed in the process at the time. All nitrification studies were conducted with diffused-air aeration sufficient to maintain a D.O. > 2.0 mg/l. All denitrification studies were performed in flexible plastic cube containers which were always filled to the top prior to putting on the plastic cap. A glass rod was fitted through a hole in the cap and extended into the container. A large magnet and magnetic stirrer were used to mix the contents. Samples were withdrawn by squeezing the container and forcing the contents out through plastic tubing attached to the glass rod. Clamping the tubing prevented any air from flowing back into the container. Samples withdrawn for NH_4^+-N or (NO_2^- + NO_3^-)-N analyses were gravity filtered through Whatman No. 1 paper immediately after collection. Typical filtration times were 1-2 minutes. Any samples taken for soluble COD analysis were vacuum filtered through Reeve Angel 984 H Glass Fiber Filters without use of the cellulose pad backing.

Since nuisance heterotrophic growths are characteristic of high SRT operation with D.C. wastewater, a few preliminary studies were undertaken to assess the potential usefulness of H_2O_2 or HOCl addition to a nitrifying activated sludge mixed liquor. The objective of these studies was to gain some idea of the dosages which could be employed to potentially obviate nuisance growth conditions without impairing the metabolism of the nitrifying organisms. None of these special studies involved any chemical addition directly to the single-stage process. Since information on the use of H_2O_2 or HOCl in nitrifying systems is scarce, the procedures and results from these few brief studies have been summarized in the Appendix.

SECTION 6

RESULTS

The major objective of this report is to summarize the kinetic and process data obtained during operation of the nine-pass reactor illustrated in Figure 2. The system was operated in this mode from May 15, 1975 to July 2, 1976. Prior to this time the single nitrification-denitrification approach was examined in two other process configurations and some preliminary data about possible system performance with flow-splitting approaches was gathered. The initial process configurations and preliminary data will be briefly summarized before proceeding to a discussion of the nine-pass reactor.

FOUR-PASS REACTOR

A four-pass oxygen activated sludge system was operated at the pilot plant during the summer of 1974. The system received D.C. secondary effluent, lime for pH control to 7.0 in the last reactor pass, and was operated to provide complete nitrification. At the end of September, the system was modified as shown in Figure 4. Inlet oxygen was fed to the void space at the top of the first pass with an external manifold used to transfer the overlying gas directly to the void space over the fourth pass where it was vented to atmosphere. No attempt was made to optimize oxygen utilization. The second and third passes were mechanically mixed. Lime addition was continued to maintain the pH in the last pass near 7.0. Although an attempt was made to maintain the D.O. between 2-4 mg/l in the aerated passes, the actual D.O. level was frequently 10-12 mg/l. This provided far from an optimum system for a single nitrification-denitrification cycle followed by terminal aeration. Nonetheless the average process performance from November 3 to December 7, 1974. resulted in the influent TKN being reduced from an average of 28.4 mg/l to an effluent TKN value of 1.5 mg/l and effluent $(NO_2^- + NO_3^-)$-N of 7.2 mg/l. This represented an overall average nitrogen removal of 70%.

At this time it was felt that there could be considerable merit in sending 60-80% of the primary effluent to the head of a plug flow biological process for nitrification with the remaining 40-20% being bypassed to a denitrification section to provide accelerated denitrification rates. A sufficiently large terminally aerated chamber could then oxidize the NH_4^+-N introduced by bypassing a portion of the sewage and result in overall nitrogen removals of 70-80%.

This concept was briefly evaluated in two kinetic studies using recycle biological solids from the four-pass system. The solids were mixed with primary effluent and aerated until all NH_4^+-N had been oxidized. Since the lag

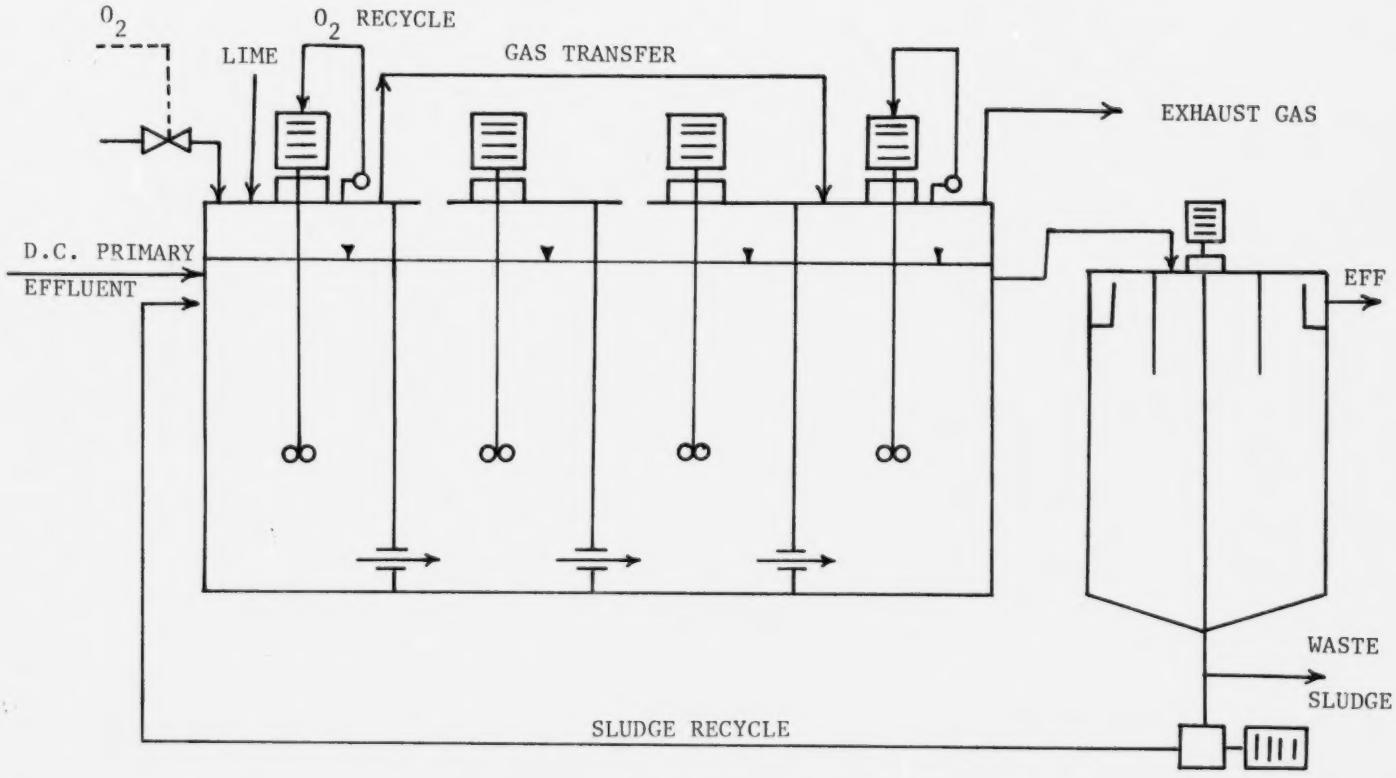

Figure 4. Schematic diagram of four-pass oxygen system.

time between sample collection and readout from the Technicon autoanalyzer was about 15-20 minutes, the aeration period necessary for complete NH_4^+-N oxidation was estimated from the first 3-4 samples and aeration was continued for a brief period beyond the calculated time required. Following aeration (D.O. of 2-6 mg/1), the sample was divided into two parts with additional primary effluent introduced into one of the two subsamples. Each of the two subsamples was then denitrified in a closed cube container as described in Section 5. A 25% primary addition corresponds to the addition of 250 ml to each initial 1000 ml of the primary. In actual practice this would correspond to splitting the influent flow with 80% going to the head of the process and 20% being added downstream after nitrification was complete. Results from one of the experiments are shown in Figure 5 and both studies are summarized in Table 1 (10/29/74 and 10/30/74). In order to centralize this type of kinetic data, Table 1 includes all results obtained throughout the project from this kind of experiment.

The first two studies indicated that if the aeration time was not excessive, the addition of moderate amounts of supplemental primary to accelerate denitrification was not especially advantageous in view of the NH_4^+-N being introduced at this point. Removal of the NH_4^+-N added to denitrification with the primary effluent would, of course, require an additional nitrification-denitrification cycle.

An additional laboratory experiment was conducted in which a single nitrification-denitrification cycle was compared with several air on-off cycles where the periods of no dissolved oxygen were selected to try to maximize the denitrification rate. Results are presented in Figures 6 and 7. The first denitrification rate in the air cycling system was almost double that of the alternate system. However, by the third cycle the rate decreased to less than the rate prevailing in the system with complete nitrification followed by denitrification. In terms of the overall time requirement for nitrogen removal, there appeared to be little advantage in going to a complex air cycling system.

EIGHT-PASS REACTOR

On the basis of these initial experiments, a decision was made to evaluate a "plug-flow" reactor operated with a single nitrification-denitrification cycle followed by terminal aeration. On December 10 the four-pass oxygen activated sludge system was expanded to an eight-pass system. Air lines were installed for aeration of passes 1, 2, and 8. Flow from the eighth pass went through a splitter box and then directly to the two clarifiers (Figure 2). The system was changed to air aeration to provide better D.O. control over that attainable by manual adjustment of the oxygen feed rates and also to eliminate the need for lime addition to maintain a pH > 6.5 in all passes.

The reactor MLVSS were maintained near 3,000 mg/1 from mid-December through February 1975. Since lime was no longer added, a large quantity of inert solids previously introduced with the lime was slowly wasted from the system, and the MLSS declined from near 7,000 mg/1 to 4,000 mg/1 by the end of January.

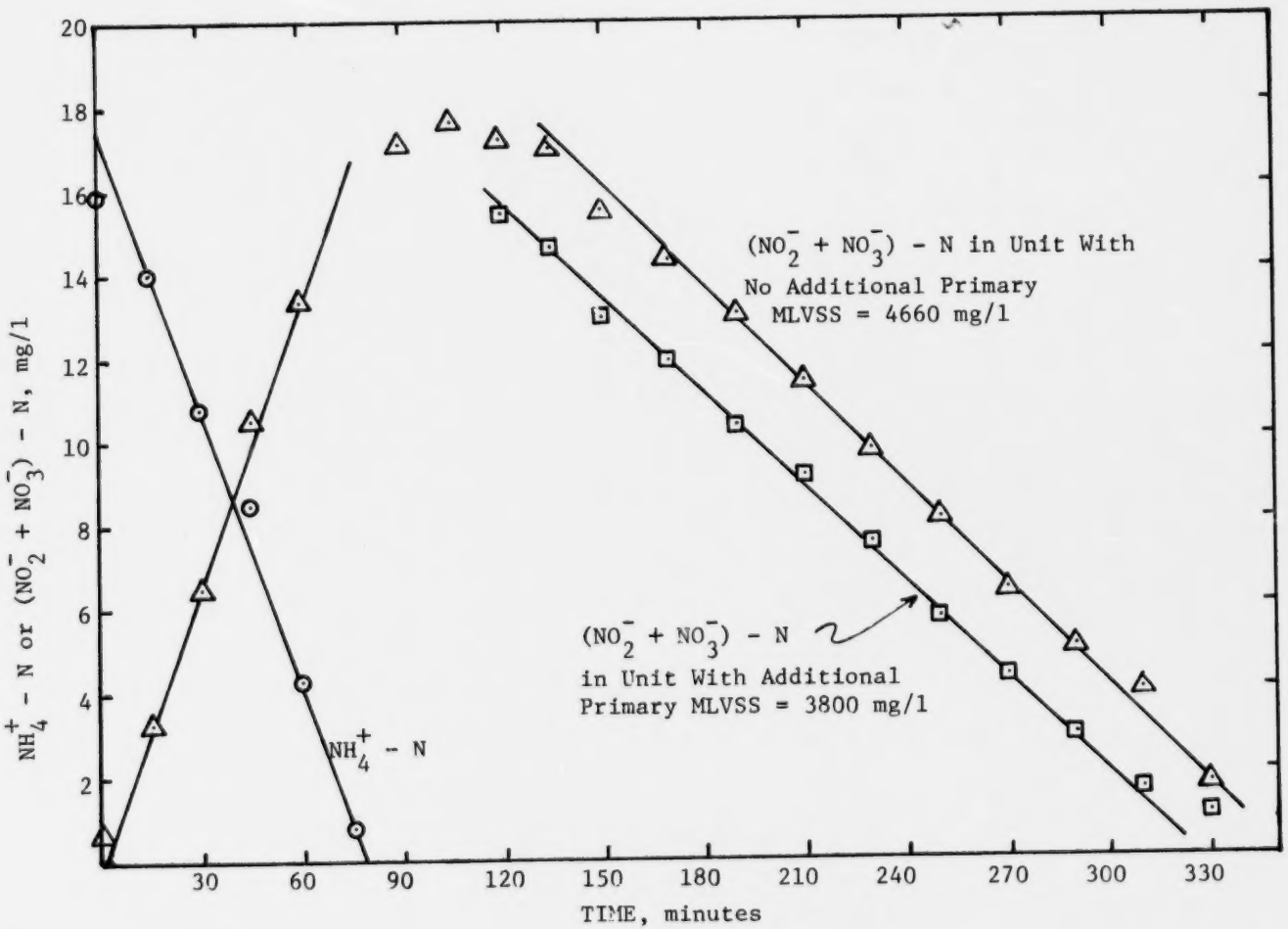

Figure 5. Laboratory kinetic study of nitrification followed by denitrification with and without supplemental primary effluent.

TABLE 1. SUMMARY OF NITRIFICATION AND DENITRIFICATION KINETIC RATES WITH AND WITHOUT SUPPLEMENTAL PRIMARY EFFLUENT.

Date	Temp oC	Initial MLVSS mg/l	Initial Primary Effluent COD mg/l	Aeration Time, min. Required for NH_4^+-N Odixation	Aeration Time, min. Actual	Nitrification Rate $\frac{mg(NO_2^- + NO_3^-)-N}{hr \cdot MLVSS}$	Denitrification Rate $\frac{mg(NO_2^- + NO_3^-)-N}{hr \cdot gMLVSS}$ Without Extra Primary	Denitrification Rate With Additional Primary Rate	Denitrification Rate With Additional Primary % Added	Initial Ratio Primary Eff. Vol. / Recycle Vol.	COD of Additional Primary Effluent mg/l	Increase in Denit. Rate With Additional Primary %
10/29/74	~23	4660	---	80	<120	2.9	1.0	1.2	20	---	---	20
10/30/74	22-23	4840	---	80	<105	2.7	0.89	1.2	50	---	---	35
11/05/74	23	3930	---	80	90	3.3	0.98	---	--	---	---	--
12/19/74	18-20	4100	202	80	85	3.4	1.3	1.5	25	2:1	173	15
01/22/75	16.5	2960	163	80	90	2.7	1.4	1.6	25	2:1	---	14
01/29/75	17	2480	135	100	110	2.9	0.90	1.1	25	2:1	135	22
02/14/75	16	2850	162	90	110	2.0	0.83	1.0	33	2:1	143	20
03/25/75	17	2540	120	90	100	2.8	0.83	0.94	33	2:1	120	13
06/25/75	26	2290	100	30	70	6.7	1.1	1.4	33	2:1	---	27
09/16/75	24.5	1520	138	40	50	6.9	1.3	1.5	11	3:1	129	15
10/16/75	23	2410	144	40	50	5.5	1.0	1.3	33	---	122	30
10/22/75	23	2100	208	70	70	4.7	1.5	1.8	33	3:1	202	20
11/20/75	21	2370	248	90	90	3.1	1.1	1.3	33	3:1	253	18
12/19/75	17	3030	---	75	80	2.4	0.94	1.1	33	3:1	---	17
02/20/76	17	2930	---	70	80	2.3	0.80	1.1	33	2:1	---	38
03/12/76	17.5	2180	---	75	90	2.9	1.1	---	--	2:1	---	--
07/02/76	25.5	2150	244	40	40	5.7	2.0	2.5	33	2:1	244	25

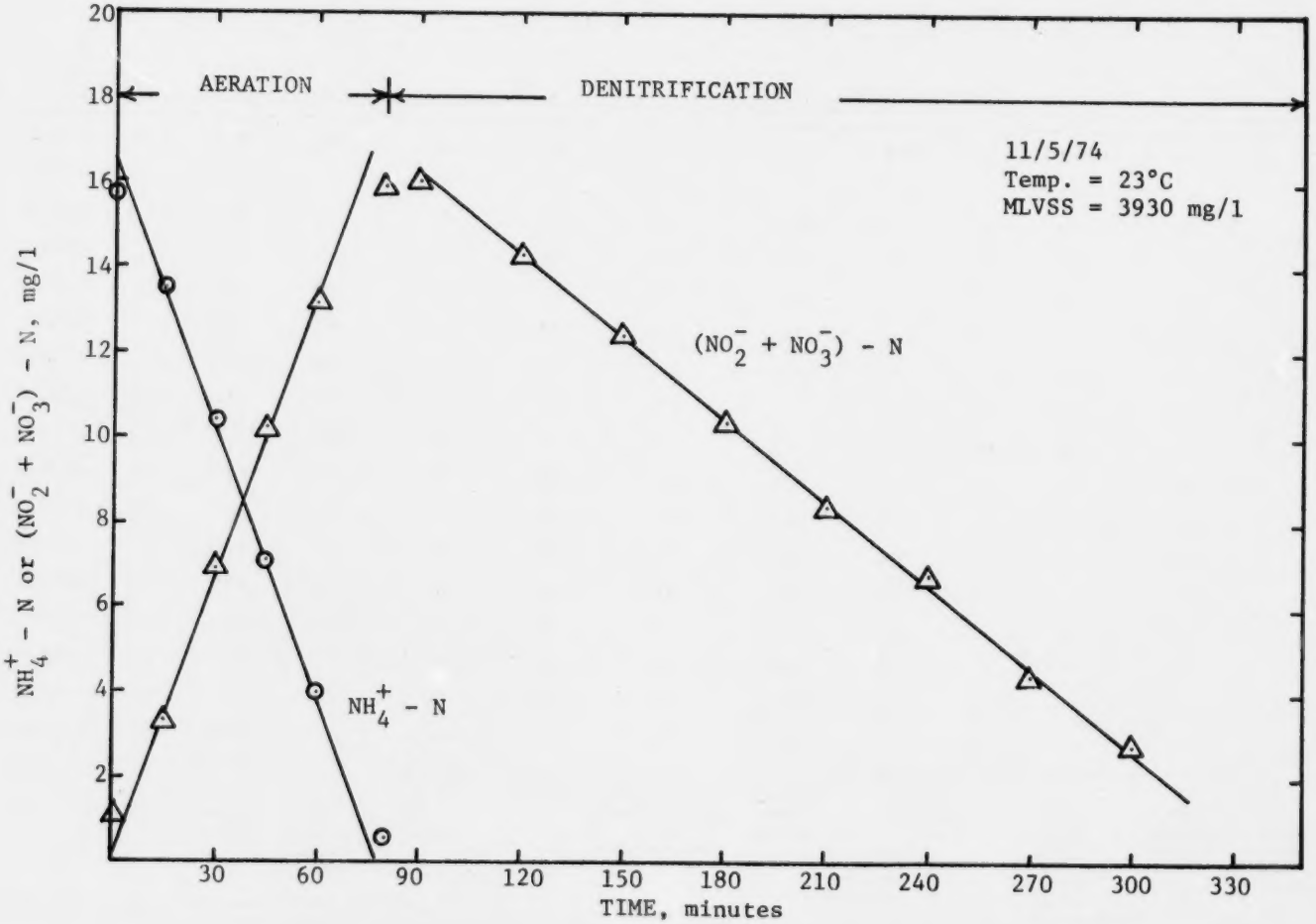

Figure 6. Laboratory kinetic study with a single nitrification-denitrification cycle.

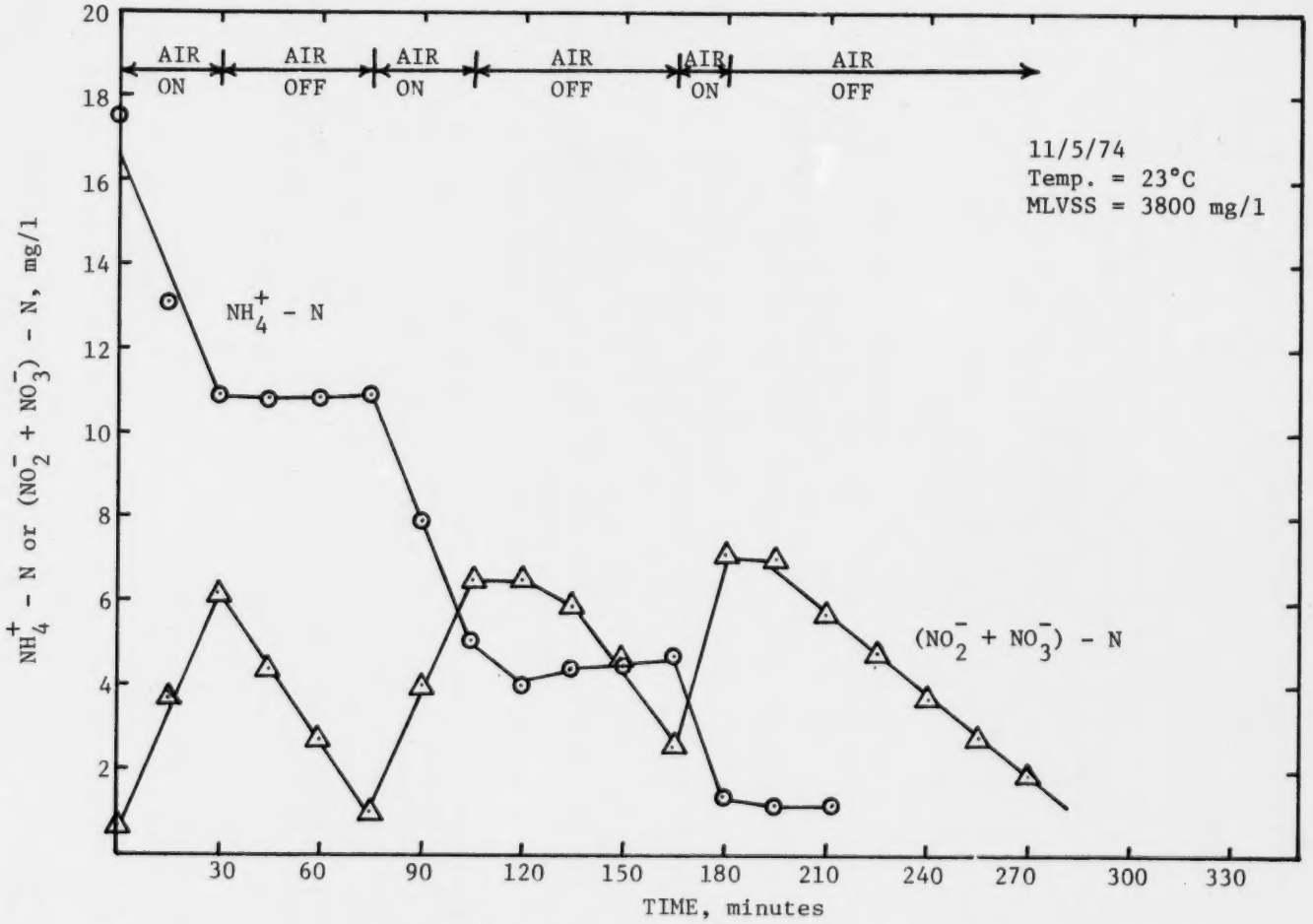

Figure 7. Laboratory kinetic study with multiple nitrification-denitrification cycles.

Prior to January 18, 1975 the main D.C. treatment plant operated with all elutriation water and thickener overflow returned back to the head of the plant. This flow was approximately 39.4 m^3/min (15 mgd) in the 790 m^3/min (300 mgd) plant. After January 18 the District modified the plant flow so that the elutriation and thickener overflow was sent directly to the head of the secondary activated sludge system. As a result, the TKN in the primary effluent available to the pilot plant decreased by an average of 8 mg/l. Because of this large change in wastewater characteristics and the system transition characteristics prevailing at this time there is not much general information to be gained from the average process performance during December or January. A few system parameters for the 30 day period of December 20-January 18 are noted in Table 2. The nitrogen removal averaged 70% with most of the effluent TKN associated with the 20 mg/l of effluent suspended solids. During this time period there was a great deal of Nocardia production and the final clarifiers were frequently covered with floating solids. This is not unique to the single stage process and has been frequently observed in secondary systems treating D.C. wastewater (16).

From January 28-February 20, 1975 the process flow was steady and averaged 171.5 m^3/day (45,300 gpd). Influent and effluent parameters were also steady during this period and a few general system characteristics have been summarized in Table 3. Each of the clarifier recycle streams was sampled individually and are so differentiated in the Table.

From February 21-23, the flow was reduced to 136.3 m^3/day (36,000 gpd) because the clarifier bed (sludge blanket) level reached the level of the effluent weirs. During the last week of February and the first two days of March digester and elutriation water was periodically sent back to the D.C. primary clarifiers while new piping was installed on the main D.C. plant. This resulted in large temporary surges in NH_4^+-N and BOD loadings and makes evaluation of composite samples meaningless. This problem was eliminated on March 3. System operation continued at steady flow until May 15.

Good system performance prevailed from March 25-April 14 and a few selected data from this period are summarized in Table 4. The heavy Nocardia concentrations which had been present up to this time produced enough foam/scum on the surfaces of the stirred passes (3,4,5,6, and 7) to essentially eliminate oxygen diffusion into the denitrification section of the reactor. However, during the last two weeks of April and the first two weeks of May, the Nocardia concentrations decreased to the point where no foam was present and excessive oxygen transfer into the denitrification passes resulted in poor nitrogen removals.

The information of primary value obtained during the period of operation of the eight-pass reactor was that derived from laboratory and/or process kinetic studies. Because of the usefulness of this information it was decided to describe the general process operation in the preceeding paragraphs.

As shown in Table 1, several additional laboratory studies were conducted with recycle solids obtained from the eight-pass reactor. Since previous studies of this type had been conducted with warm wastewater ($\sim 23^{\circ}C$), there remained the question as to whether a flow-splitting arrangement might not

TABLE 2. SELECTED CHARACTERISTICS FOR THE EIGHT PASS REACTOR FROM DECEMBER 20, 1974 TO JANUARY 18, 1975

Parameter	Value	
Influent Flow, m^3/day	153.3	
Influent Flow, gpd	40,500	
Total Reactor Detention Time, hrs	9.6	
Aerated Reactor Detention Time, hrs	3.6	
MLVSS (Standard Deviation), mg/l	3,040 (95)	
F/M Ratio, $gBOD_5$ Applied/g MLVSS	0.10	
	Influent	Effluent
BOD, mg/l	124	13
COD, mg/l	262	31
TKN, mg/l	28.7	2.4
$(NO_2^- + NO_3^-)$-N, mg/l	0	6.0
Temperature, °C	17.6	--

TABLE 3. SELECTED CHARACTERISTICS FOR THE EIGHT PASS REACTOR FROM JANUARY 28 TO FEBRUARY 20, 1975

Parameter	Value	
Influent Flow, m^3/day	171.5	
Influent Flow, gpd	45,300	
Total Reactor Detention Time, hrs	8.6	
Aerated Reactor Detention Time, hrs	3.2	
MLSS (Std. Dev.), mg/l	4,130 (156)	
MLVSS (Std. Dev.), mg/l	2,840 (108)	
F/M Ratio, $gBOD_5$ Applied/day/g MLVSS	0.10	
Recycle No. 1 VSS (Std. Dev.), mg/l	7,950 (256)	
Recycle No. 1 TKN (Std. Dev.), mg/l	745 (55)	
Recycle No. 2 VSS (Std. Dev.), mg/l	8,170 (288)	
Recycle No. 2 TKN (Std. Dev.), mg/l	787 (61)	
Percent TKN in Recycle VSS (No. 1), %	9.4	
Percent TKN in Recycle VSS (No. 2), %	9.6	
	Influent	Effluent
BOD, mg/l	104	10.7
COD, mg/l	225	27.5
TKN, mg/l	19.7	1.7
NH_4^+-N, mg/l	15.4	0.3
$(NO_2^- + NO_3^-)$-N, mg/l	0	2.5
SS, mg/l	89	17
Temp, °C	16.7	--

TABLE 4. SELECTED CHARACTERISTICS FOR THE EIGHT PASS REACTOR FROM MARCH 23 TO APRIL 14, 1975

Parameter	Value
Influent Flow, m^3/day	161.3
Influent Flow, gpd	42,600
Total Reactor Detention Time, hrs	9.1
Aerated Reactor Detention Time, hrs	3.4
MLSS (Std. Dev.), mg/l	4,250 (96)
MLVSS (Std. Dev.), mg/l	2,890 (117)
F/M Ratio, $gBOD_5$ Applied/day/ g MLVSS	0.10
Recycle No. 1 VSS (Std. Dev.), mg/l	7,110 (470)
Recycle No. 1 TKN (Std. Dev.), mg/l	713 (104)
Recycle No. 1 P (Std. Dev.), mg/l	266 (23.3)
Recycle No. 2 VSS (Std. Dev.), mg/l	7,290 (265)
Recycle No. 2 TKN (Std. Dev.), mg/l	739 (148)
Recycle No. 2 P (Std. Dev.), mg/l	277 (21.7)
Percent TKN in Recycle VSS (No. 1), %	10.0
Percent TKN in Recycle VSS (No. 2), %	10.1
Percent P in Recycle VSS (No. 1), %	3.7
Percent P in Recycle VSS (No. 2), %	3.8

	Influent	Effluent
BOD, mg/l	112	8.5
COD, mg/l	225	23.5
TKN, mg/l	21.7	1.5
NH_4^+ - N, mg/l	16.1	0.2
$(NO_2^- + NO_3^-)$-N, mg/l	0	3.4
SS, mg/l	87	11
Temp, °C	16.9	--

prove necessary under wintertime conditions. In the five laboratory studies conducted from December 1974 through March 1975 the aeration time was closely controlled to be only slightly in excess of that required for "complete" (< 0.5 mg/1) NH_4^+-N oxidation. In all cases, the addition of 25 or 33% more primary effluent did accelerate the subsequent denitrification rate, but the increase was only 15-20%. It was felt that this small increase in rate was not worth the penalty of introducing NH_4^+-N into the third pass of the eight-pass reactor by splitting the influent flow to both these reactor passes.

With a perfect plug flow reactor, one could theoretically control the aeration period to be just sufficient to complete the oxidation of the incoming NH_4^+-N with the remainder of the tankage used for denitrification. Of course, in actual practice this is not possible. Therefore, an additional question at this time was what happened to the subsequent denitrification rate when the initial aeration period was extended beyond the time required for NH_4^+-N oxidation. This was briefly investigated in the laboratory by aerating a large sample of recycle solids and primary effluent and transferring subsamples to closed stirred containers for denitrification at various times during the aeration period. All results from this type of laboratory experiment have been centralized in Table 5. Because of a temperature increase in the unit removed after 110 minutes on February 13 (temperature bath malfunction), the denitrification rate may be somewhat higher than normal. This study (and the others which will be discussed later) did indicate that the length of the aeration period was closely connected with the ensuing denitrification rate.

The last major question remaining at this time was whether or not these laboratory studies were indicative of what was actually occurring in the pilot plant system. Samples from each of the eight passes were collected at various times on January 23 and January 30 and analyzed for NH_4^+-N and $(NO_2^- + NO_3^-)$-N. Results of the $(NO_2^- + NO_3^-)$-N determinations are presented in Table 6. In both cases from 1.5 to 4 mg/1 of NH_4^+-N remained unoxidized in the second pass. It is immediately obvious that aeration of pass 8 was creating aerobic conditions/backmixing in pass 7. The increase in measured $(NO_2^- + NO_3^-)$-N levels between passes 6 and 7 was paralled by a decrease in the measured NH_4^+-N concentration. The $(NO_2^- + NO_3^-)$-N levels in passes 2 and 3 were also the "same" in all cases, which reflected the influent mixed liquor (to pass 3) at 2-4 mg/1 D.O. in addition to any mixing between this aerated and stirred set of passes. The differences in $(NO_2^- + NO_3^-)$-N levels between passes 1 and 2, 3 and 4, 4 and 5, and 5 and 6, can be used to calculate system kinetic rates by assuming a series arrangement of completely mixed reactors. The results of these calculations are summarized in Table 7. The estimated nitrification kinetic rates of 2.9 and 2.7 mg N/hr/g VSS agree very closely with the results obtained in the laboratory studies on January 22 and 29 (Table 1). There was sufficient exogenous NH_4^+-N left in pass 2 of the reactor to treat the kinetic rate in this system independently of NH_4^+-N concentration. The denitrification kinetic rates were also calculated by taking the difference between passes and these rates also agree well with the denitrification rates without added primary shown in Table 1 for the same time period.

TABLE 5. SUMMARY OF REDUCTION IN DENITRIFICATION KINETIC RATES FOLLOWING EXTENDED AERATION

Date	Temp °C	Initial MLVSS mg/l	Initial Primary Effluent COD mg/l	Aeration time, min. Required for NH_4^+ - N Oxidation	Aeration time, min. Actual	Nitrification Rate $\frac{mg(NO_2^- + NO_3^-)-N}{hr \cdot gMLVSS}$	Denitrification Rate $\frac{mg(NO_2^- + NO_3^-)-N}{hr \cdot gMLVSS}$	Initial Ratio $\frac{\text{Primary Eff. Vol}}{\text{Recycle Vol.}}$
2/13/75	17-22				110		1.2	
	16.5	2840	166	90		2.2		2:1
	17.0				155		0.67	
9/10/75					57		1.9	
	25	1420	117	38	102	8.6	1.4	3:1
					147		1.4	
10/2/75					45		1.3	
	22.5	1810	--	37	105	6.1	0.89	3:1
					165		0.72	
2/26/76					60		0.96	
	17	3280	--	60	105	2.2	0.79	2:1
					150		0.74	
6/25/76					35		1.3	
	24.5	2270	--	27		5.8		2:1
					95		1.0	

TABLE 6. $(NO_2^- + NO_3^-)$-N CONCENTRATIONS IN THE NINE PASS REACTOR AT SELECTED TIMES ON JANUARY 23 AND JANUARY 30, 1975

		$(NO_2^- + NO_3^-)$-N, mg/l								
Date	Time	Inf.	Pass 1	Pass 2	Pass 3	Pass 4	Pass 5	Pass 6	Pass 7	Pass 8
1/23/75	1100	0	4.9	10.2	9.7	7.8	---	---	---	---
	1155	0	---	---	---	---	6.1	4.6	6.3	6.8
	1355	0	4.2	10.1	10.5	8.7	6.8	5.5	6.9	7.5
	1530	0	---	9.9	9.9	---	---	---	7.5	8.2
1/30/75	1300	0	4.5	9.8	9.4	7.2	4.9	3.2	4.6	4.5
	1500	0	4.1	9.4	9.2	7.3	5.0	3.5	4.5	5.0

Date	1/23/75	1/30/75
Average Influent Flow, l/min	121.5	117.3
Total Recycle Flow, l/min	62.4	62.4
Average MLSS, mg/l	4,000	4,080
Average MLVSS, mg/l	2,800	2,765

TABLE 7. NITRIFICATION AND DENITRIFICATION KINETIC RATES IN THE NINE PASS REACTOR ON JANUARY 23 AND JANUARY 30, 1975

Date	Time	Passes	$(NO_2^- + NO_3^-)$-N Difference mg/l	Average Difference mg/l	Kinetic Rate $mg(NO_2^- + NO_3^-)$-N / hr . g MLVSS
1/23	1100	2-1	5.3	5.6	2.9
	1355	2-1	5.9		
1/30	1300	2-1	5.3	5.3	2.7
	1500	2-1	5.3		
1/23	1100	3-4	1.9	1.85	0.96
	1355	3-4	1.8		
1/23	1355	4-5	1.9	1.9	0.98
1/23	1155	5-6	1.5	1.4	0.72
	1355	5-6	1.3		
1/30	1300	3-4	2.2	2.05	1.05
	1500	3-4	1.9		
1/30	1300	4-5	2.3	2.3	1.17
	1500	4-5	2.3		
1/30	1300	5-6	1.7	1.6	0.82
	1500	5-6	1.5		

Studies of this type were also used to verify that the poor denitrification performance during the last two weeks of April and the first two weeks of May was the result of oxygen transfer into the stirred passes after the foam/scum layer disappeared. A sample withdrawn from the fifth pass denitrified in a sealed container at a rate of 0.7 mg N/hr/g VSS but pass to pass measurements showed that there was virtually no change in the (NO_2^- + NO_3^-)-N levels in the reactor.

NINE-PASS REACTOR

In an effort to overcome some of the mixing/oxygen diffusion problems, the system configuration was changed on May 15 to the nine-pass configuration shown in Figure 2. This eliminated the backmixing/aeration problem between the seventh and eighth passes. Fortunately, the Nocardia concentration began to rebuild in the middle of May and the resulting foam/scum in passes 3-7 effectively eliminated the oxygen diffusion problem for the remainder of the project. Since the mixed liquor exited from the "top" of pass 8, the scum could not build up on this pass.

The system was operated at a steady average flow of 167.3 m^3/day (44,200 gpd) from May 28 through July 9. Reactor solids and effluent TKN and (NO_2^- + NO_3^-)-N values are shown on a daily basis in Figure 8. Other system parameters are summarized in Tables 8 and 9. The nitrification-denitrification performance of the system was excellent with an average residual NH_4^+-N concentration of 0.1 mg/l and an average residual (NO_2^- + NO_3^-)-N concentration of just 0.75 mg/l. From a practical point of view, the system delivered as good an effluent quality during this period as one could realistically hope for with the present flow arrangement.

The MLSS declined from around 4,000 mg/l during the first half of the period summarized in Table 8 to about 3,400 mg/l during July. Also the clarifier bed levels exhibited a gradual reduction during June and July. The system SRT based on the total solids in the nine passes of the reactor was 28 days and it was 9.2 days based on the solids in the aerated passes (1, 2 and 9) only. The observed net solids production for this period was 0.58 g SS/g BOD_5 applied and 0.40 g VSS/g BOD_5 applied. In view of the general decline in reactor solids and the clarifier bed level, these sludge production numbers reflect some wasting from "storage."

If the influent mass of phosphorus is divided by the effluent plus waste total mass, the ratio is 1.12. Considering that there was a decline in solids concentration, one would expect to calculate a ratio slightly less than 1. There were no difficulties with the influent flow meter during this period and the deviation of the P mass balance from unity presumably reflects mostly error in the P determination. The materials balance approach is useful in single stage nitrification-denitrification since it enables the amount of nitrogen removed by denitrification to be calculated. If one assumes a perfect N mass balance, the amount of nitrogen removed through denitrification averaged 12.9 mg/l. Taking the nitrification rate of 6.7 mg (NO_2^- + NO_3^-)-N/hr/g MLVSS from 6/25/75 (Table 1) in conjunction with a 79 l/min (21 gpm) recycle flow and a 117 l/min (31 gpm) influent flow, it can be calculated that up to 22.7 mg/l of NH_4^+-N could be oxidized (neglecting concentration

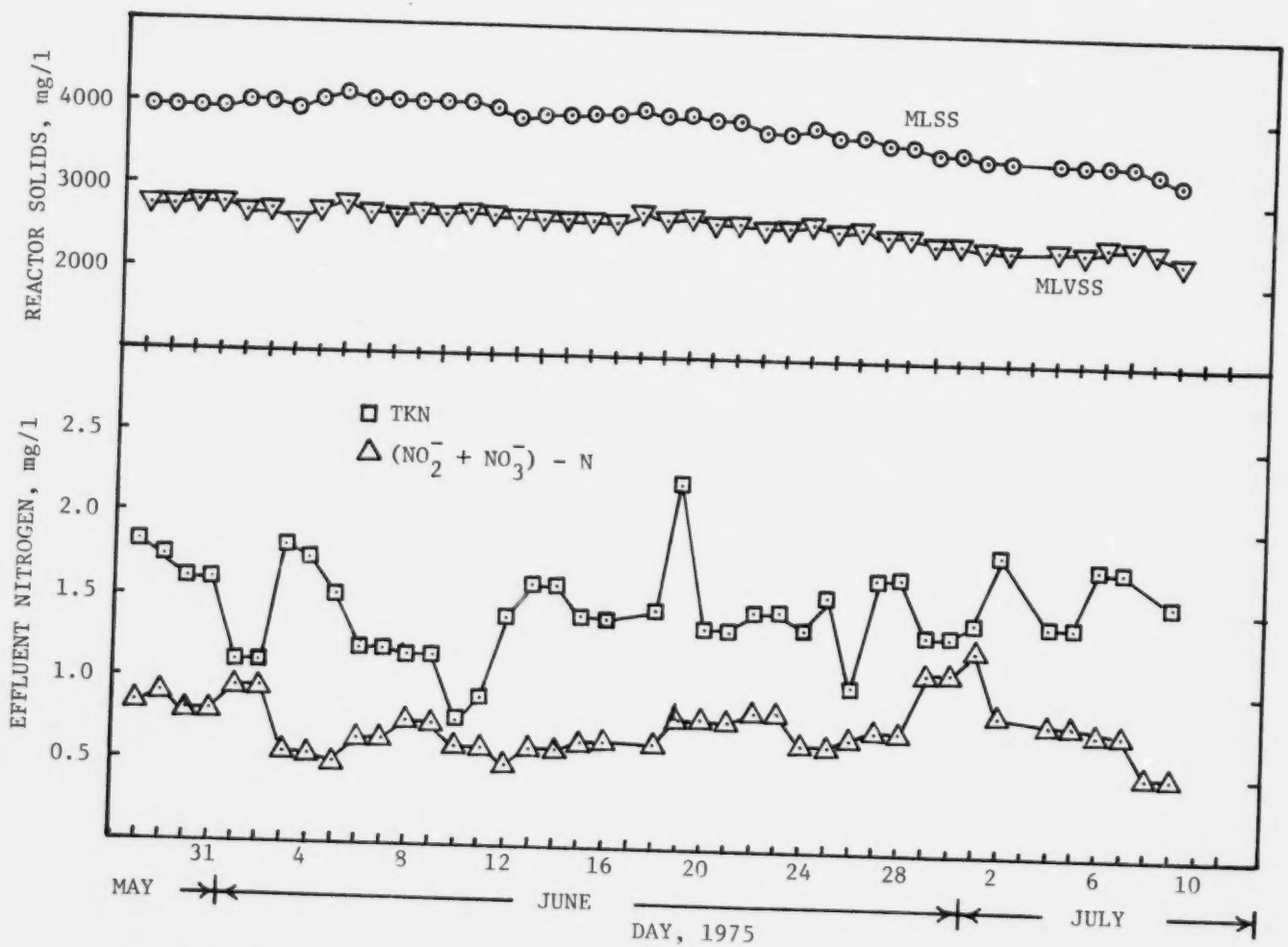

Figure 8. Reactor solids levels and effluent TKN and $(NO_2^- + NO_3^-)$-N levels from May 28 to July 9, 1976.

TABLE 8. PROCESS CHARACTERISTICS FOR THE NINE PASS REACTOR FROM MAY 28 TO JULY 9, 1975

Parameter	Value or Average	Standard Deviation
Total Reactor Detention Time, hrs	9.8	
Aerated Reactor Detention Time, hrs	3.2	
Influent Flow, gpd	44,200	
Influent Flow, m^3/day	167.3	
Total Recycle Flow, gpm	19-23	
Total Recycle Flow, l/min	72-87	
Clarifier Overflow Rates, gpd/ft^2	285	
Clarifier Overflow Rates, m/day	11.6	
MLSS, mg/l	3820	249
MLVSS, mg/l	2610	145
SVI, ml/gm	250	10
F/M Ratio, gBOD_5 Applied/day/g MLVSS	0.09	
Recycle Suspended Solids (No. 1), mg/l	9270	665
Recycle Volatile Suspended Solids (No. 1), mg/l	6300	340
Recycle TKN (No. 1), mg/l	625	73
Recycle P (No. 1), mg/l	231	24
Recycle Suspended Solids (No. 2), mg/l	8790	398
Recycle Volatile Suspended Solids (No. 2), mg/l	5940	252
Recycle TKN (No. 2), mg/l	587	67
Recycle P (No. 2), mg/l	215	22
Percent P in Recycle VSS (No. 1), %	3.7	
Percent P in Recycle VSS (No. 2), %	3.6	
Percent TKN in Recycle VSS (No. 1), %	9.9	
Percent TKN in Recycle VSS (No. 2), %	9.9	

TABLE 9. INFLUENT AND EFFLUENT CHARACTERISTICS FOR THE NINE PASS REACTOR FROM MAY 28 TO JULY 9, 1975

Parameter	Influent		Clarifier No. 1 Effluent		Clarifier No. 2 Effluent	
	Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation
BOD, mg/l	96	15.5	8.9	1.6	9.8	2.1
Inhibited BOD, mg/l	--	--	3.6	1.1	4.3	1.4
COD, mg/l	198	23.8	23.8	4.5	28.0	5.5
SS, mg/l	79	16.6	11.3	2.5	14.1	6.2
VSS, mg/l	60	11.8	8.0	2.4	9.9	5.5
TKN, mg/l	18.0	2.2	1.3	0.31	1.6	0.44
NH_4^+ - N, mg/l	13.0	1.1	0.1	0.08	0.1	0.08
$(NO_2^- + NO_3^-)$-N, mg/l	0	--	0.8	0.17	0.7	0.17
Total P, mg/l	4.8	0.59	3.2	0.52	3.3	0.46
Temp., °C	24.5	1.3				

dependence at low concentrations) in the first two reactor passes at MLVSS of 2610 mg/l. On July 1 a series of measurements were made of the NH_4^+-N and (NO_2^- + NO_3^-)-N levels in each pass. The influent NH_4^+-N concentration during the period of the measurements was so low that nitrification was nearly completed in the first pass. The average denitrification rate from passes 3 to 4 and 4 to 5 (passes with NO_3^--N > 1.0 mg/l) was 1.3 mg (NO_2^- + NO_3^-)-N/hr/g MLVSS and this rate also agrees well with the results of laboratory measurements on 6/25 (Table 1).

Because of the excellent system response under steady state flow conditions, it was decided to place more stress on the system by imposing a diurnal flow cycle. On July 10, the diurnal flow pattern shown in Figure 9 was imposed on the system. This flow pattern varies from 76 l/min (20 gpm) to 170 l/min (45 gpm) and averages approximately 170 m^3/day (45,000 gpd). The system was operated with a diurnally varying flow until September 22, 1975.

The relationships between the flow meter, the flow recorder and the actual process flow are summarized in Table 10. There was essentially no trouble with the Data-Trak system so the metered flow to the system consistently followed the pattern shown in Figure 9. From the initiation of the diurnal flow through about September 2, there were no major discrepancies between metered, recorded and actual flow. Since the relationships among the three values changed at each flow level on any given day, it was extremely difficult to correct the recorded values and determine the true flow. Even with no major problems during August, the recorded flow averaged 162.4 m^3/day (42,900 gpd) for the first 18 days and 184.7 m^3/day (48,800 gpd) for the last 13 days. The flow problem was particularly bad during the middle of September where the actual flow was 38-45 l/min (10-12 gpm) higher than the recorded or metered flow. At this time, the flow varied from about 114 to 227 l/min (30 to 60 gpm) although the flow pattern (time of maximum and minimum flows) continued to follow that shown in Figure 1. Also at this time the flow was being underrecorded by around 60.6 m^3/day (16,000 gpd).

In view of all the difficulties encountered in trying to record the actual flow while operating with the diurnal pattern, the best approach to data analysis appeared to be to treat the data as one large block. Operation over the 74-day period is summarized in Tables 11 and 12. The average influent flow was determined by using the information in Table 10 to arrive at a "best guess" of the real average flow. The value of 185.5 m^3/day (49,000 gpd) was used in all calculations involving flow, e.g. loading, SRT, etc.

Washington, D.C. experienced a very wet summer in 1975 and stormwater flows/infiltration comprised a large part of the total plant flow during this period. The influent BOD_5 only averaged 81 mg/l and the influent TKN was just 16.9 mg/l for the 74-day period summarized in Tables 11 and 12. The variation in reactor MLSS and MLVSS is shown in Figure 10. Each value represents the average from three separate composite samples (passes 1, 5 and 9) and should represent a realistic average in spite of the diurnal flow. It can be seen that the solids levels gradually declined until mid-August

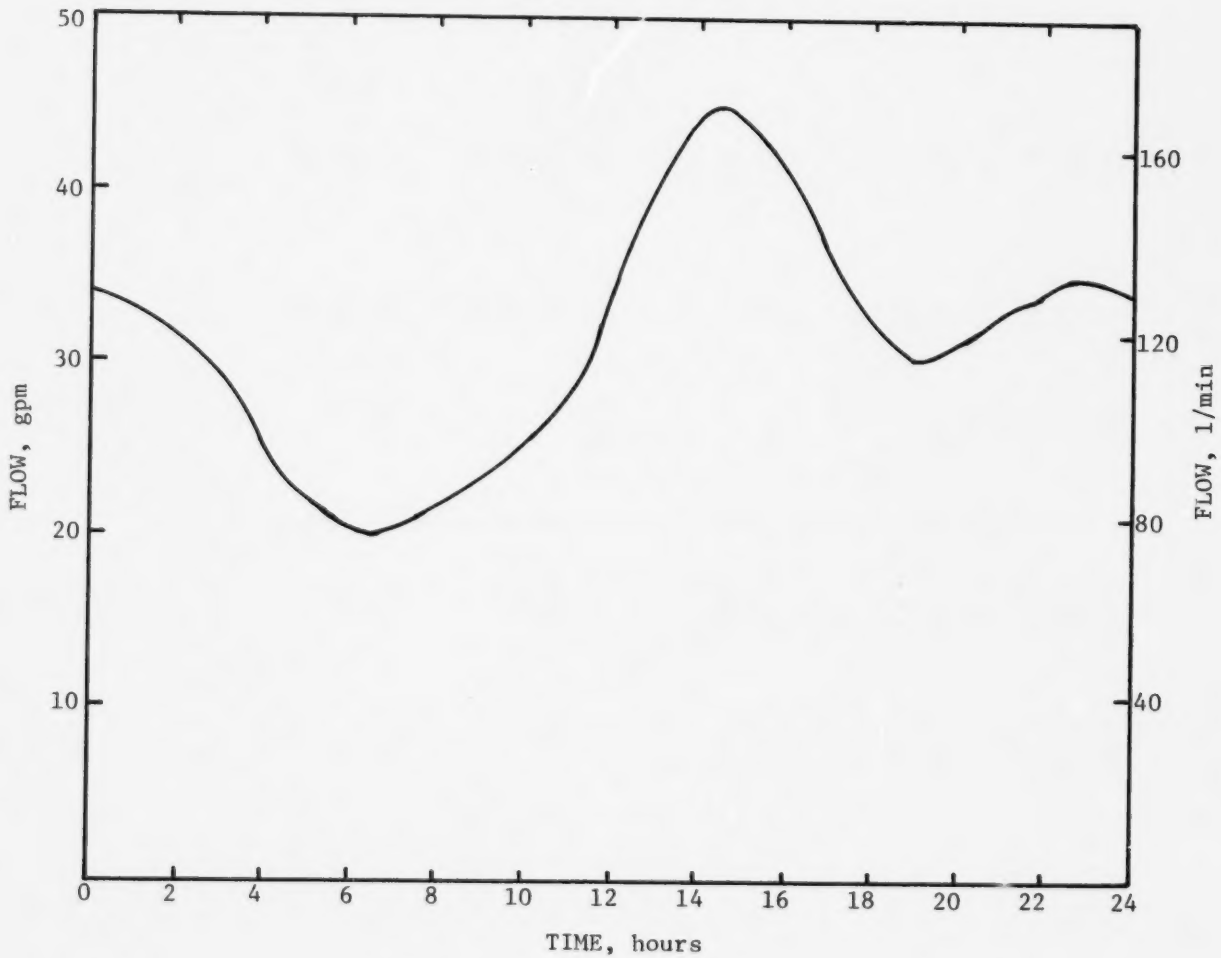

Figure 9. Diurnal flow pattern.

TABLE 10. RELATIONSHIPS AMONG FLOW METER, FLOW RECORDER AND ACTUAL FLOW DURING OPERATION WITH A DIURNAL FLOW

Date	Flow, gpm			Date	Flow, gpm		
	Meter	Recorded	Actual		Meter	Recorded	Actual
7/10	22	20	23.3	8/25	48	51	47.5
	33	32	33.7		30	30	31.8
	44	44	42.0		10	8	13.4
7/14	25	23	28.3	9/2	55	58	59.4
	10	8	14.9		33	33	35.7
					20	19	22.8
7/21	31	30	32.0	9/8	51	53	57.1
	41	39	38.8		42	44	48.3
					26	25	29.1
7/28	10	6	11.8	9/15	50	53	66
	25	22	24.0		41	44	55.5
					31	32	43.0
					21	21	30.5
8/4	20	18	21.1	9/22	56	58	56.1
	30	27	28.1		36	37	38.6
					25	24	28.8
8/11	40	38	35.6				
	19	15	18.4				
8/18	50	46	45.7				
	40	37	38.3				
	30	27	30.3				
	20	16	21.8				

TABLE 11. PROCESS CHARACTERISTICS FOR THE NINE PASS REACTOR FROM JULY 11 TO SEPTEMBER 22, 1975

Parameter	Value or Average	Standard Deviation
Total Reactor Detention Time, hrs	8.8	
Aerated Reactor Detention Time, hrs	2.9	
Influent Flow, m^3/day	185.5	
Influent Flow, gpd	49,000	
Total Recycle Flow, l/min	68-76	
Total Recycle Flow, gpm	18-20	
Clarifier Overflow Rates, m/day	12.8	
Clarifier Overflow Rates, gpd/ft^2	314	
MLSS, mg/l	2830	393
MLVSS, mg/l	1900	255
F/M Ratio, g BOD_5 Applied/day/g MLVSS	0.12	
Recycle Suspended Solids(No. 1), mg/l	7210	1285
Recycle Volatile Suspended Solids (No. 1), mg/l	4780	825
Recycle TKN (No. 1), mg/l	480	97
Recycle P (No. 1), mg/l	188	35
Recycle Suspended Solids (No. 2), mg/l	7210	985
Recycle Volatile Suspended Solids (No. 2), mg/l	4810	615
Recycle TKN (No. 2), mg/l	500	78
Recycle P (No. 2), mg/l	193	30
Percent P in Recycle VSS (No. 1), %	3.9	
Percent P in Recycle VSS (No. 2), %	4.0	
Percent TKN in Recycle VSS (No. 1), %	10.0	
Percent TKN in Recycle VSS (No. 2), %	10.4	

TABLE 12. INFLUENT AND EFFLUENT CHARACTERISTICS FOR THE NINE PASS REACTOR FROM JULY 11 TO SEPTEMBER 22, 1975

Parameter	Influent		Clarifier No. 1 Effluent		Clarifier No. 2 Effluent	
	Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation
BOD, mg/l	81.0	14.2	7.8	2.2	8.8	2.7
Inhibited BOD, mg/l	---	---	2.8	1.3	3.4	1.9
COD, mg/l	187	27.4	22.1	2.9	25.5	4.4
SS, mg/l	88	15.5	11.2	4.9	15.3	5.8
VSS, mg/l	64	12.5	7.4	3.3	10.5	4.7
TKN, mg/l	16.9	2.7	1.4	0.70	1.4	0.49
NH_4^+ - N, mg/l	11.9	2.3	0.1	0.15	0.1	0.14
$(NO_2^- + NO_3^-)$-N, mg/l	---	---	0.88	0.22	0.85	0.22
Total P, mg/l	4.7	0.78	2.9	0.52	2.9	0.39
Temp., °C	26.2	1.1				

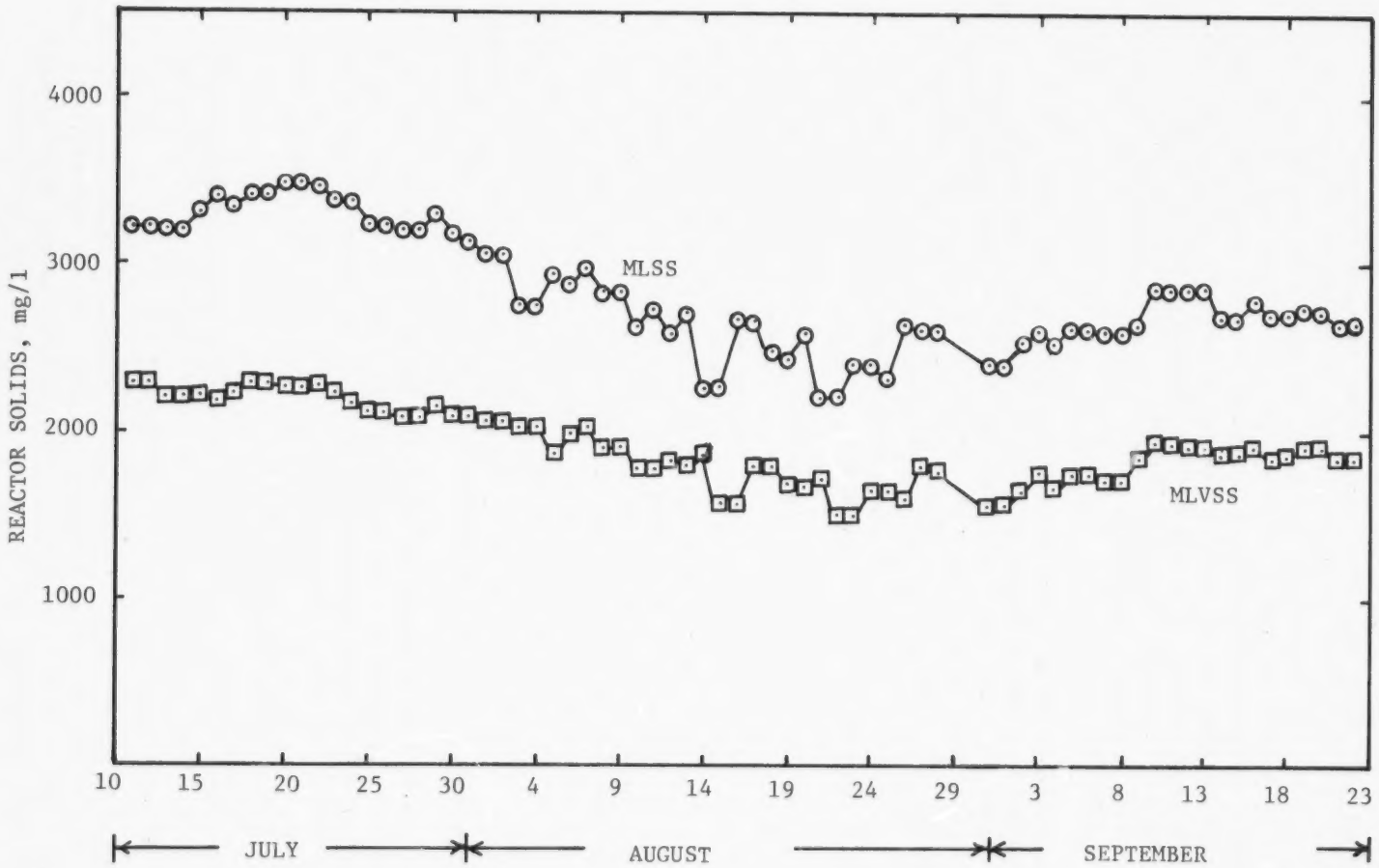

Figure 10. Reactor solids levels from July 11 to September 22, 1975.

and then held generally steady for the remainder of the period summarized. Underflow wasting was varied to maintain the desired MLSS levels and varied from 757 l/day (200 gpd) from July 11-31 down to no wasting between August 27-September 8. Using the solids actually deliberately wasted each day in conjunction with the waste rate for each day yields an average daily waste for the 74-day period of 2040 g VSS/day. At 49,000 gpd and 9.0 mg/l VSS in the effluent, the overflow wasting amounted to 1670 g VSS/day. This indicates that calculations of SRT and sludge production are extremely sensitive to effluent solids levels. The presence of Nocardia caused erratic solids levels in the effluent as shown in Figure 11. The average SRT was 35 days with net solids production values of 0.37 g SS/g BOD_5 applied and 0.25 g VSS/g BOD_5 applied.

Neither the influent or effluent composite sample volumes were flow proportioned. Continuous TOC analyses of primary effluent feed were available during part of September (furnished by W. Schuk) and selected results from 5 day's analyses are presented in Table 13. The reported TOC values were those at the times the six daily grab samples for the laboratory composite sample were taken. It can be seen that there is no difference between the flow proportioned averages and the arithmetic averages when following the flow pattern shown in Figure 9.

The daily average effluent TKN and $(NO_3^- + NO_3^-)$-N values are shown in Figure 12. The variability in effluent TKN reflects the variability in effluent suspended solids since the NH_4^+-N concentrations were extremely low at all times (average of 0.1 mg/l). The $(NO_2^- + NO_3^-)$-N levels averaged 0.9 mg/l over this 74-day period and once again these residual levels were as low as one can realistically hope to attain with this type of single stage process. Furthermore the effluent quality was essentially the same as observed at steady flow, thus indicating that the system could handle reasonable flow variations and still perform well. At nitrification rates of 7 mg $(NO_2^- + NO_3^-)$-N/hr/g MLVSS (Table 1), one could accept NH_4^+-N concentrations of 18 mg/l at 50 gpm and 1900 mg/l VSS and still attain "complete" nitrification prior to denitrification. Again it should be noted that this calculation neglects concentration dependent kinetics encountered with low exogenous NH_4^+-N levels.

Two kinetic studies were performed with the recycle solids during the period of diurnal flow operation. Results are presented in Tables 1 and 5. Once again it was observed that there was no obvious advantage in switching to a flow-splitting arrangement, and overaeration beyond that required for nitrification still resulted in satisfactory denitrification rates for operation at the warm wastewater temperatures.

On September 23, 1975, the primary effluent flow to the single stage system was set at a steady 132 l/min (35 gpm). $FeCl_3$ addition to the ninth pass of the reactor was initiated with the dosage set at 35 mg/l. This is equivalent to an Fe^{+3} dosage of 12.0 mg/l or an Fe:P mole ratio of 1.3 at an influent P concentration of 5 mg/l. Parallel dual-media filters were placed downstream from the No. 1 clarifier in early October. $FeCl_3$ addition was continued until December 2, 1975. The next period of process and kinetic data to be considered will summarize the period of $FeCl_3$ addition and filter operation.

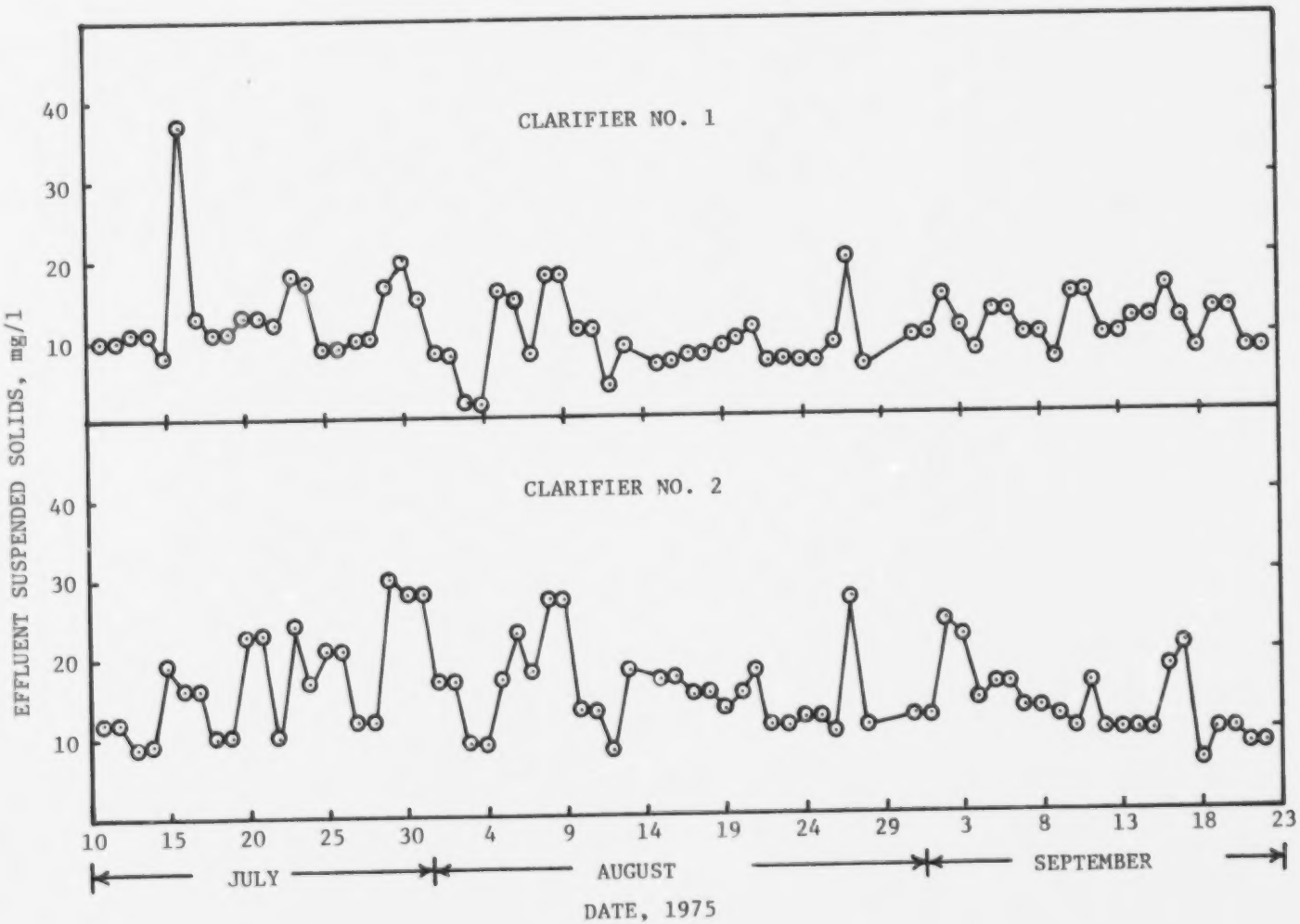

Figure 11. Effluent suspended solids from July 11 to September 22, 1975.

TABLE 13. COMPARISON OF TOC LOADING BASED ON ARITHMETIC VS. FLOW-PROPORTIONED AVERAGES

Flow gpm	Flow l/min	Time	Influent TOC, mg/l Date 9/10	9/11	9/12	9/13	9/17
20	76	0630	53	59	55	54	60
26	98	1030	37	40	37	38	40
45	170	1430	52	43	47	39	43
31	117	1830	65	61	60	64	65
35	132	2230	72	68	59	68	72
30	113	0230	68	71	60	58	69
Arithmetic Average			57.8	57.0	53.0	53.5	58.1
Flow Proportioned Average			58.5	56.4	53.0	53.1	57.6

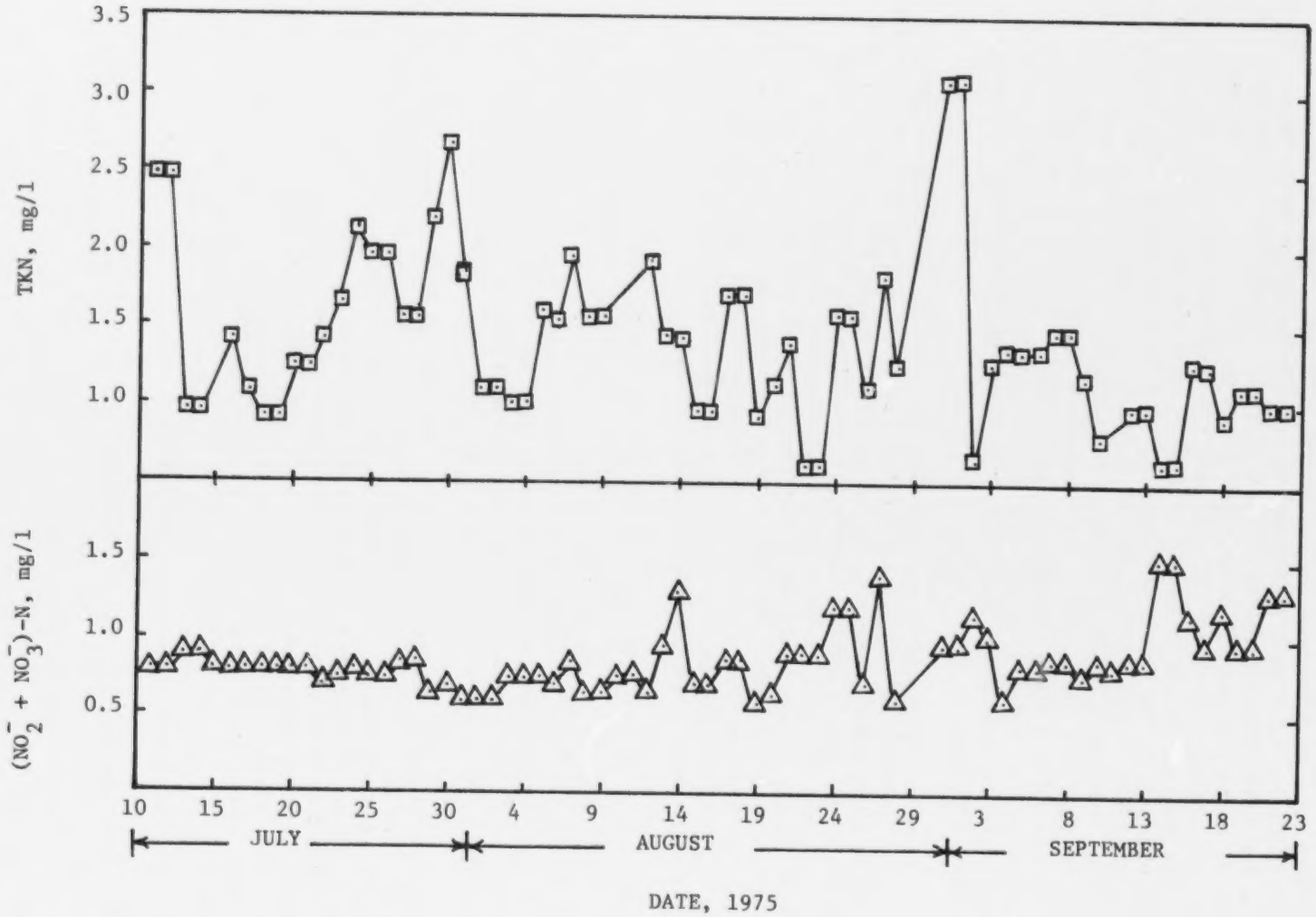

Figure 12. Effluent TKN and $(NO_2^- + NO_3^-)$-N from July 11 to September 22, 1975.

The $FeCl_3$ had an immediate impact on the effluent P concentration which decreased to < 0.5 mg/1 by September 24. There was no noticeable impact on the nitrification-denitrification cycle. Operation during the remainder of September and all of October posed no problems. The influent flow was always near 132 1/min (35 gpm) and the chemical feed rate was very stable. Placing the chemical feed in the last pass did not depress the mixed liquor pH below 6.5. As shown in Figure 13, the MLSS increased considerably during this period. Filters "N" and "P" (arbitrary designations) were placed in operation on October 6. All effluent from the No. 1 clarifier was directed to an overflowing 208 1 (55 gal) drum from which the filter influents were pumped at a steady 19 1/min (5 gpm) to each filter. Sample collection was initiated after the first operating cycle was completed. The filter samples were composited in accordance with the same schedule as all other influent and effluent samples.

Operation during November and December 1-2 was not as stable as during October. By November 18, the clarifier bed levels were very near the surface and periodic flow reductions from 132 1/min to 113 1/min (35 to 30 gpm) were made whenever the clarifier bed started to overflow the weirs. This flow reduction caused the beds to drop back below the effluent weirs and collection of effluent samples was postponed a few minutes if necessary until the bed had dropped below the weir. No filter data are reported for any period where the clarifier bed overflow resulted in a surge of solids onto the filters. Also during November and December 1-2, the chemical feed rates were somewhat more erratic as were the effluent P concentrations.

The changes in waste rates, reactor solids concentrations, clarifier bed levels, flow rate, etc. preclude any period from being considered representative of steady-state operation. The reactor VSS were deliberately increased in anticipation of cold wastewater temperatures which did not develop. In fact, the wastewater temperature was still 20°C at the end of November. The increase in MLVSS was accompanied by the considerably higher MLSS which included the effects of the chemical sludge from $FeCl_3$ addition.

The system characteristics have been summarized in four separate ways in Tables 14 thru 19. Very heavy rains at the end of September produced an abnormally weak wastewater for several days. This is reflected in the low average influent loading for the period of September 24-October 31. This period was summarized separately because the flow and chemical doses were most stable during this time. The 35 mg/1 $FeCl_3$ dose resulted in an average residual phosphorus concentration of less than 0.5 mg/1. Even during the period with somewhat more variability in flow and dosage (November 1-December 2), the average residual phosphorus concentration was only 0.64 mg/1; this also reflects the lower Fe:P mole ratio which resulted from the higher average influent phosphorus concentrations.

Operation during the period of October 9-November 20 has also been summarized separately since this is the period of good filter operation. There were enough temporary bed upsets on the No. 1 clarifier after November 20 to make it impossible to calculate solids loadings to the filters. Results from the filter operation during the 43-day period of

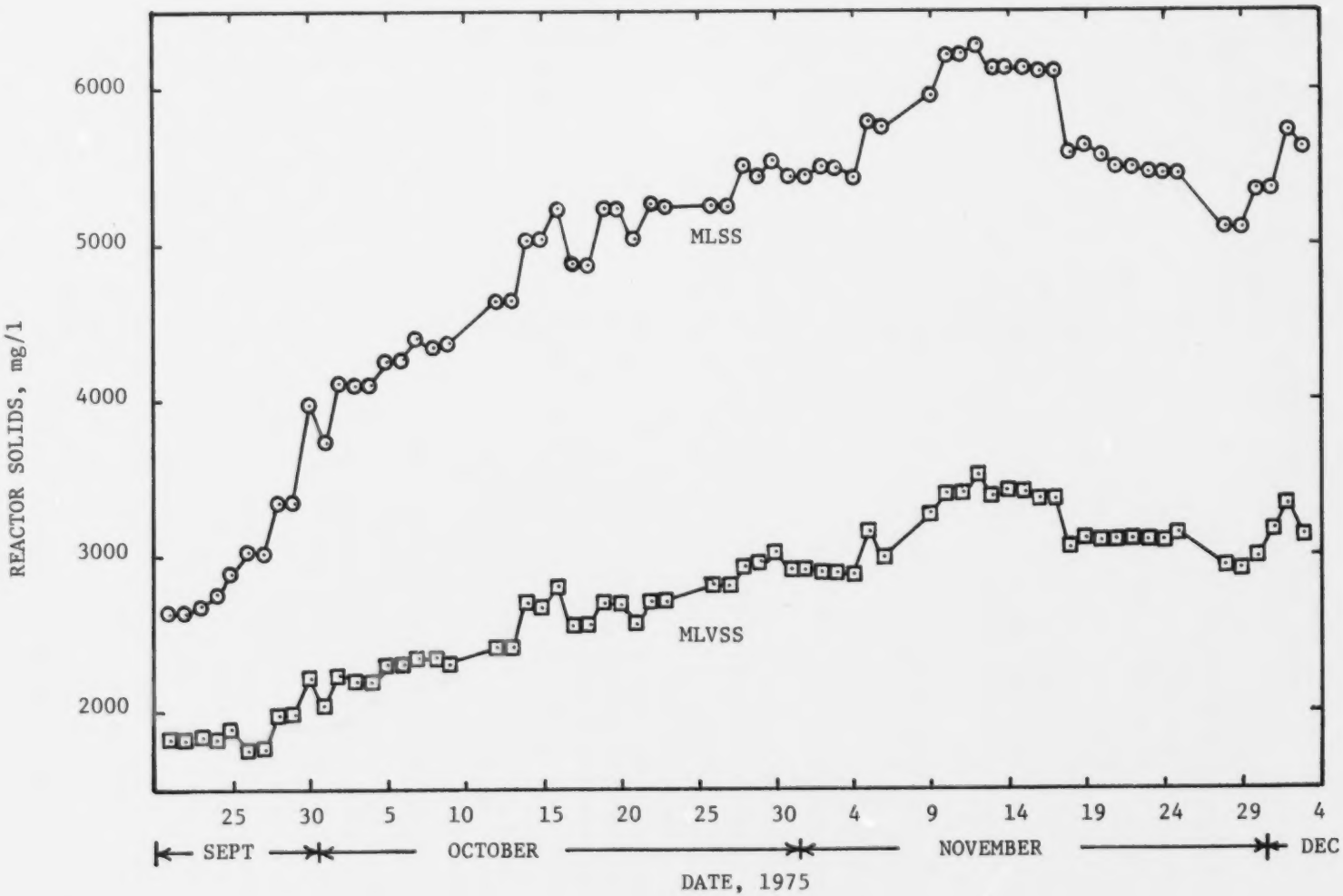

Figure 13. Reactor solids levels from September 23 to December 2, 1975.

TABLE 14. SUMMARIES OF PROCESS CHARACTERISTICS WITH THE NINE PASS REACTOR FOR THREE PERIODS DURING SEPTEMBER-DECEMBER, 1975

Parameter	Value or Average	Standard Deviation
September 24 - December 2 (70 Days)		
Total Reactor Detention Time, hrs	8.4	
Aerated Reactor Detention Time, hrs	2.8	
Influent Flow, gpd	51,300	
Influent Flow, m^3/day	194.2	
Total Recycle Flow, gpm	18-20	
Total Recycle Flow, l/min	68-76	
Clarifier Overflow Rates, gpd/ft^2	329	
Clarifier Overflow Rates, m/day	13.4	
MLSS, mg/l	5020	878
MLVSS, mg/l	2740	471
F/M Ratio, g BOD_5 Applied/day/g MLVSS	0.09	
$FeCl_3$ Dose*, mg/l	34.1	4.2
Fe:P Mole Ratio	1.35	
September 24 - October 31 (38 Days)		
Total Reactor Detention Time, hrs	8.1	
Aerated Reactor Detention Time, hrs	2.7	
Influent Flow, gpd	53,300	
Influent Flow, m^3/day	201.8	
Total Recycle Flow, gpm	18-20	
Total Recycle Flow, l/min	68-76	
Clarifier Overflow Rates, gpd/ft^2	342	
Clarifier Overflow Rates, m/day	13.9	
MLSS, mg/l	4510	817
MLVSS, mg/l	2430	369
F/M Ratio, g BOD_5 Applied/day/g MLVSS	0.10	
$FeCl_3$ Dose*, mg/l	34.7	2.0
Fe:P Mole Ratio	1.55	
October 9 - November 20 (43 Days)		
Total Reactor Detention Time, hrs	8.7	
Aerated Reactor Detention Time, hrs	2.9	
Influent Flow, gpd	49,600	
Influent Flow, m^3/day	187.8	
Total Recycle Flow, gpm	18-20	
Total Recycle Flow, l/min	68-76	
Clarifier Overflow Rates, gpd/ft^2	320	
Clarifier Overflow Rates, m/day	13.0	
MLSS, mg/l	5450	495
MLVSS, mg/l	2920	327
F/M Ratio, g BOD_5 Applied/day/g MLVSS	0.09	
$FeCl_3$ Dose*, mg/l	34.9	4.8
Fe:P Mole Ratio	1.25	

*Based on Average Influent Flow for Period

TABLE 15. INFLUENT AND EFFLUENT CHARACTERISTICS FOR THE NINE PASS REACTOR FROM SEPTEMBER 24 TO DECEMBER 2, 1975

Parameter	Influent		Clarifier No. 1 Effluent		Clarifier No. 2 Effluent	
	Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation
BOD, mg/l	88.4	16.6	4.8	1.8	4.7	1.3
Inhibited BOD, mg/l	-	-	2.8	1.1	2.7	0.72
COD, mg/l	191	34.0	19.2	2.3	20.2	3.3
SS, mg/l	88	18.6	10.9	3.6	12.9	4.7
VSS, mg/l	64	10.0	6.3	2.3	7.2	2.9
NH_4^+-N, mg/l	12.3	2.4	0.2	0.20	0.2	0.20
$(NO_2^- + NO_3^-)$-N, mg/l	-	-	0.8	0.30	0.8	0.26
Total P, mg/l	4.8	1.2	0.52	0.17	0.55	0.16
Temp., ^oC	21.8	1.2				

TABLE 16. INFLUENT AND EFFLUENT CHARACTERISTICS FOR THE NINE PASS REACTOR FROM SEPTEMBER 24 TO OCTOBER 31, 1975

Parameter	Influent		Clarifier No. 1 Effluent		Clarifier No. 2 Effluent	
	Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation
BOD, mg/l	79.1	16.1	4.4	1.2	4.9	1.3
Inhibited BOD, mg/l	-	-	2.3	0.55	2.4	0.49
COD, mg/l	175	34.2	18.6	2.0	19.5	2.3
SS, mg/l	84	17.1	10.9	3.54	14.0	3.96
VSS, mg/l	61	9.2	6.0	2.3	7.5	2.3
NH_4^+-N, mg/l	11.8	2.9	0.2	0.15	0.2	0.19
$(NO_2^- + NO_3^-)$-N, mg/l	-	-	0.8	0.29	0.8	0.28
Total P, mg/l	4.3	1.1	0.43	0.10	0.48	0.12
Temp., ^oC	22.6	0.50				

TABLE 17. INFLUENT AND EFFLUENT CHARACTERISTICS FOR THE NINE PASS REACTOR FROM OCTOBER 9 TO NOVEMBER 20, 1975

Parameter	Influent		Clarifier No. 1 Effluent		Clarifier No. 2 Effluent	
	Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation
BOD, mg/l	91.2	12.7	4.6	1.7	4.6	1.4
Inhibited BOD, mg/l	-	-	2.5	0.9	2.5	0.63
COD, mg/l	206	20.9	19.1	1.9	20.1	2.3
SS, mg/l	86	13.6	11.0	3.6	13.1	4.9
VSS, mg/l	65	9.3	6.3	2.4	7.3	3.2
NH_4^+-N, mg/l	13.0	1.3	0.2	0.23	0.2	0.23
$(NO_2^- + NO_3^-)$-N, mg/l	-	-	0.8	0.36	0.8	0.30
Total P, mg/l	5.4	0.98	0.58	0.17	0.60	0.13
Temp., ^oC	22.0	0.91				

TABLE 18. PROCESS CHARACTERISTICS FOR THE NINE PASS REACTOR FROM NOVEMBER 1 TO DECEMBER 2, 1975

Parameter	Value or Average	Standard Deviation
Total Reactor Detention Time, hrs	8.8	
Aerated Reactor Detention Time, hrs	2.9	
Influent Flow, gpd	48,900	
Influent Flow, m^3/day	185.1	
Total Recycle Flow, gpm	18-20	
Total Recycle Flow, l/min	68-76	
Clarifier Overflow Rates, gpd/ft^2	314	
Clarifier Overflow Rates, m/day	12.8	
MLSS, mg/l	5680	357
MLVSS, mg/l	3140	205
F/M Ratio, g BOD_5 Applied/day/g MLVSS	0.09	
Recycle Suspended Solids (No. 1), mg/l	16,100	1062
Recycle Volatile Suspended Solids (No. 1), mg/l	8800	691
Recycle P (No. 1), mg/l	711	80
Recycle Suspended Solids (No. 2), mg/l	17,360	1601
Recycle Volatile Suspended Solids (No. 2), mg/l	9410	793
Recycle P (No. 2), mg/l	711	88
Percent P in Recycle VSS (No. 1)	8.1	
Percent P in Recycle VSS (No. 2)	7.6	
$FeCl_3$ Dose*, mg/l	33.3	5.0
Fe:P Mole Ratio	1.15	

* Based on Average Influent Flow for Period

TABLE 19. INFLUENT AND EFFLUENT CHARACTERISTICS FOR THE NINE PASS REACTOR FROM NOVEMBER 1 TO DECEMBER 2, 1975

Parameter	Influent		Clarifier No. 1 Effluent		Clarifier No. 2 Effluent	
	Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation
BOD, mg/l	100	7.9	5.2	2.3	4.4	1.2
Inhibited BOD, mg/l	-	-	3.2	1.4	3.0	0.84
COD, mg/l	212	20.1	20.0	2.5	21.0	4.2
SS, mg/l	93	19.6	10.8	3.7	11.5	5.1
VSS, mg/l	68	9.9	6.6	2.4	6.9	3.5
NH_4^+-N, mg/l	12.7	1.1	0.2	0.23	0.2	0.20
$(NO_2^- + NO_3^-)$-N, mg/l	-	-	0.8	0.32	0.7	0.22
Total P, mg/l	5.5	1.0	0.63	0.17	0.64	0.17
Temp., ^oC	20.8	1.0				

October 9-November 20 are summarized in Tables 20 and 21. The No. 1 clarifier effluent was sampled again after being pumped to the top of the filters and both results have been summarized in Table 20. The effluent quality from the two filters was identical. As indicated in Table 21, the average run with filter "P" was 72 hours with a minimum run length of 50 hours. Average solids capture per run was also 50% greater than with filter "N." These results are consistent with previous observations when the two media were compared (17). It can be seen that an excellent effluent quality was obtained.

There were no problems with $FeCl_3$ addition in terms of nitrification-denitrification performance. The effluent NH_4^+-N and $(NO_2^- + NO_3^-)$-N levels continued to be very low and not significantly different than those levels observed from June to September during the period of no $FeCl_3$ addition. During the last five days of operation considered here (after 65 days of $FeCl_3$ addition) the residual NH_4^+-N averaged 0.2 mg/l and the effluent $(NO_2^- + NO_3^-)$-N concentration was 0.9 mg/l. The clarifier bed level problem at the end of November (compounded by a 20% underrecording of influent flow for a week) was minor and would not have existed at just slightly lower hydraulic loadings. In retrospect, the solids levels were also higher than needed because the anticipated drop in wastewater temperature did not occur.

Four laboratory studies were also conducted with the recycle solids during the period of $FeCl_3$ addition. The potential advantage of influent flow-splitting appeared to be minimal (Table 1). The denitrification rate was again shown to be dependent on the length of the aeration period (Table 5).

On December 3, 1975, the $FeCl_3$ addition was terminated and the influent flow increased to 132 l/min (35 gpm). At this time the intent was to stress the system during wintertime operation. Beginning on December 25, the clarifier bed levels began to drop dramatically and the level in the No. 2 clarifier decreased 2.1m (7 ft) over a 3-day period. The system was examined repeatedly over the next few days but the problem was not discovered until January 6. At this time, it was found that one of the drive-box gears on the No. 1 clarifier had worn to the point that the clarifier scraper mechanism was no longer turning. This was missed in the earlier inspections of the system since the drive motor was still running as usual. The influent flow was reduced to 64 l/min (17 gpm) and all process effluent was diverted to the No. 2 clarifier. The No. 1 clarifier was pumped down during the night of the 6th. Examination of the No. 1 clarifier on the morning of the 7th revealed that all of the "lost" solids were lying on the bottom of the clarifier. The visual appearance and odor characteristics of these solids was such that it was decided to return them to the reactor rather than waste them to drain. A replacement gear was installed and the flow was increased to 114 l/min (30 gpm). This resulted in a 3000 mg/l increase in reactor MLSS, and the effluent NH_4^+-N levels which had averaged 4 mg/l from January 4-6 were reduced to 0.1 mg/l by January 10, 1976.

The process characteristics from December 4-December 23 have been summarized in Tables 22 and 23. The effluent P concentrations slowly rose over this period from about 1 mg/l on December 4 to near 3 mg/l by December 23. The wastewater temperatures decreased from 20°C to 16.5°C by

TABLE 20. EFFECT OF FILTRATION ON THE CLARIFIED EFFLUENT FROM THE NINE PASS REACTOR FROM OCTOBER 9 TO NOVEMBER 20, 1975

Parameter	Clarifier No. 1 Effluent		Filter Influent		Filter "N" Effluent		Filter "P" Effluent	
	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
BOD, mg/l	4.6	1.7	5.0	1.7	1.6	0.86	1.5	0.73
Inhibited BOD, mg/l	2.5	0.9	2.9	1.0	1.4	0.62	1.4	0.61
SS, mg/l	11.0	3.6	14.8	5.1	2.2	0.77	2.2	0.95
VSS, mg/l	6.3	2.4	8.3	2.8	1.6	0.56	1.6	0.79
P, mg/l	0.58	0.17	0.64	0.19	0.25	0.09	0.25	0.08
NH_4^+-N, mg/l	0.2	0.23	0.2	0.27	0.2	0.20	0.2	0.18
$(NO_2^- + NO_3^-)$-N, mg/l	0.8	0.36	0.8	0.31	0.9	0.30	0.9	0.29

TABLE 21. FILTER OPERATION AND PERFORMANCE

Parameter	Filter "N"	Filter "P"
Number of Runs	22	14
Mean Length of Run (Std. Dev.), hrs	47.5 (9.7)	71.5 (16.2)
Minimum Run Length, hrs	34	50
Maximum Run Length, hrs	68	104
Filtration Rate, gpm/ft^2 (cm/min)	5.0 (20.4)	5.0 (20.4)
Mean Headloss to Backwash, inches (cm)	104 (264)	98 (249)
Maximum Headloss to Backwash, inches (cm)	114 (290)	109 (277)
Minimum Headloss to Backwash, inches (cm)	95 (241)	78 (198)
Average Initial Headloss (Std. Dev.), inches	11.6 (1.4)	8.7 (1.4)
Average Initial Headloss (Std. Dev.), cm	29.5 (3.6)	22.1 (3.6)
Average Solids Capture, lb/ft^2/run	1.50	2.26
Average Solids Capture, kg/m^2/run	7.32	11.03
Filter "N"		
64 cm anthracite	ES = 1.3 mm	UC = 1.5
38 cm silica sand	ES = 0.65 mm	UC = 1.4
Filter "P"		
64 cm anthracite	ES = 2.0 mm	UC = 1.5
38 cm silica sand	ES = 0.9 mm	UC = 1.4

TABLE 22. PROCESS CHARACTERISTICS FOR THE NINE PASS REACTOR FROM DECEMBER 4-23, 1975

Parameter	Value or Average	Standard Deviation
Total Reactor Detention Time, hrs	8.2	
Aerated Reactor Detention Time, hrs	2.7	
Influent Flow, gpd	52,700	
Influent Flow, m^3/day	199.5	
Total Recycle Flow, gpm	19	
Total Recycle Flow, l/min	72	
Clarifier Overflow Rates, gpd/ft^2	338	
Clarifier Overflow Rates, m/day	13.8	
SVI, ml/gm	191	11.3
MLSS, mg/l	5210	417
MLVSS, mg/l	3220	167
Total Reactor SRT, days	20	
F/M Ratio, g BOD_5 Applied/day/g MLVSS	0.10	
Recycle Suspended Solids (No. 1), mg/l	15,510	931
Recycle Volatile Suspended Solids (No. 1), mg/l	9590	322
Recycle P (No. 1), mg/l	640	68
Recycle Suspended Solids (No. 2), mg/l	16,300	456
Recycle Volatile Suspended Solids (No. 2), mg/l	10,110	492
Recycle P (No. 2), mg/l	656	77
Percent P in Recycle VSS (No. 1), %	6.7	
Percent P in Recycle VSS (No. 2), %	6.5	

TABLE 23. INFLUENT AND EFFLUENT CHARACTERISTICS FOR THE NINE PASS REACTOR FROM DECEMBER 4-23, 1975

Parameter	Influent		Clarifier No. 1 Effluent		Clarifier No. 2 Effluent	
	Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation
BOD, mg/l	115	17.1	5.6	1.1	6.0	1.7
Inhibited BOD, mg/l	-	-	3.7	0.5	3.9	1.0
COD, mg/l	238	19.6	23.8	3.9	23.3	4.1
SS, mg/l	98	15.1	12.1	7.5	11.4	7.1
VSS, mg/l	76	10.9	6.8	4.3	6.2	4.8
NH_4^+-N, mg/l	13.0	0.91	0.3	0.17	0.3	0.12
$(NO_2^- + NO_3^-)$-N, mg/l	-	-	1.6	0.4	1.5	0.4
Total P, mg/l	5.4	0.46	2.0	0.49	2.0	0.33
Temp., ^oC	18.2	0.9				

the 23rd. The combination of a decline in wastewater temperature and a higher process loading resulted in a residual $(NO_2^- + NO_3^-)$-N concentration of 1.6 mg/l. This occurred because the initial aeration period was insufficient to oxidize all of the NH_4^+-N and this unoxidized fraction was not oxidized until reaching the terminal aeration chamber.

There was a gradual decline in the MLSS levels during the 20-day period from December 4-23 as the chemical sludge was slowly wasted from the system. The volatile suspended solids concentration and clarifier bed levels remained generally uniform but the calculated 20-day SRT and net VSS production of 0.48 g VSS/g BOD_5 applied may not be very close to the true equilibrium values at the average loading of 0.10 g BOD_5 applied/g MLVSS. The one laboratory kinetic evaluation conducted during December (Table 1) produced a typical response. A nitrification rate of 2.4 mg N/hr/g VSS, MLVSS of 3220 mg/l, and an influent flow of 139 l/min (36.6 gpm) allow a maximum $(NO_2^- + NO_3^-)$-N formation of 14.3 mg/l (undiluted with recycle) in the first two passes. This was very close to the average influent NH_4^+-N concentration in the composited samples. Although the hydraulic loading was constant during this time, the NH_4^+-N loading cycled with the hourly changes in wastewater strength (Table 13) resulting in insufficient aeration time in the first two passes for complete NH_4^+-N oxidation during part of each day.

The interruption in system operation because of the clarifier drive failure makes it extremely difficult to interpret the results after the system was repaired and returned to normal operation. The question that cannot be answered is whether the period of time in which a substantial fraction of the biological solids lay in the No. 1 clarifier was sufficient to alter the normal relationships between viability of nitrifying organisms, viability of heterotrophic organisms, and system MLVSS. Hence the next period of operation to be summarized must be considered with this question in mind.

System operation from January 16-February 10 is summarized in Tables 24 and 25. This time frame was selected since the effluent characteristics and reactor solids were quite uniform during this 26-day period. The aeration time in passes 1 and 2 was insufficient to oxidize all incoming NH_4^+-N. The higher than normal P content in the recycle solids indicates that there were still chemical solids in the system from the $FeCl_3$ addition and of course a substantial fraction of the solids which had lain at the bottom of the No. 1 clarifier. The total reactor SRT was 33 days with net VSS production of 0.38 g VSS/g BOD_5 applied. The system continued to nitrify and denitrify well during this cold weather operation, but little more can be prudently said.

The effluent NH_4^+-N concentration decreased in mid-February to $\sim$ 0.3 mg/l. The process temperature, influent flow rate and volumetric waste rate were stable from February 26-April 5, 1976, and operating results from this period are summarized in Tables 26 and 27. The nitrification rates on 2/20/76 (Table 1) and 2/26/76 (Table 5) were quite close to those seen the year before on 2/13/75 (Table 5) and 2/14/75 (Table 1) at the same wastewater temperatures. This would indicate that the response during the

TABLE 24. PROCESS CHARACTERISTICS FOR THE NINE PASS REACTOR FROM JANUARY 16 TO FEBRUARY 10, 1976

Parameter	Value or Average	Standard Deviation
Total Reactor Detention Time, hrs	9.5	
Aerated Reactor Detention Time, hrs	3.1	
Influent Flow, gpd	45,700	
Influent Flow, m^3/day	173.0	
Total Recycle Flow, gpm	19	
Total Recycle Flow, l/min	72	
Clarifier Overflow Rates, gpd/ft^2	293	
Clarifier Overflow Rates, m/day	11.9	
SVI, ml/gm	182	4.5
MLSS, mg/l	5380	196
MLVSS, mg/l	3660	141
Total Reactor SRT, days	33	
F/M Ratio, g BOD_5 Applied/day/g MLVSS	0.08	
Recycle Suspended Solids (No. 1), mg/l	14,370	1022
Recycle Volatile Suspended Solids (No. 1), mg/l	9720	654
Recycle P (No. 1), mg/l	506	89
Recycle Suspended Solids (No. 2), mg/l	14,190	801
Recycle Volatile Suspended Solids (No. 2), mg/l	9580	504
Recycle P (No. 2), mg/l	506	46
Percent P in Recycle VSS (No. 1), %	5.2	
Percent P in Recycle VSS (No. 2), %	5.3	

TABLE 25. INFLUENT AND EFFLUENT CHARACTERISTICS FOR THE NINE PASS REACTOR FROM JANUARY 16 TO FEBRUARY 10, 1976

Parameter	Influent		Clarifier No. 1 Effluent		Clarifier No. 2 Effluent	
	Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation
BOD, mg/l	114	20.5	6.9	3.0	7.6	2.4
Inhibited BOD, mg/l	-	-	4.6	1.8	5.1	1.5
COD, mg/l	230	26.2	26.0	4.8	28.1	8.9
SS, mg/l	98	13.2	11.8	6.1	12.2	7.1
VSS, mg/l	76	13.0	7.5	4.5	7.6	6.2
NH_4^+-N, mg/l	11.7	1.8	0.8	0.5	0.8	0.4
$(NO_2^- + NO_3^-)$-N, mg/l	0.3	0.3	1.6	0.4	1.4	0.4
Total P, mg/l	5.5	0.98	2.7	0.36	2.7	0.46
Temp., ^oC	15.3	0.55				

TABLE 26. PROCESS CHARACTERISTICS FOR THE NINE PASS REACTOR FROM FEBRUARY 26 TO APRIL 5, 1976

Parameter	Value or Average	Standard Deviation
Total Reactor Detention Time, hrs	10.2	
Aerated Reactor Detention Time, hrs	3.3	
Influent Flow, gpd	42,400	
Influent Flow, m^3/day	160.5	
Total Recycle Flow, gpm	19.3	
Total Recycle Flow, l/min	73	
Clarifier Overflow Rates, gpd/ft^2	272	
Clarifier Overflow Rates, m/day	11.1	
SVI, ml/gm	180	12
MLSS, mg/l	4900	517
MLVSS, mg/l	3530	346
Total Reactor SRT, days	35	
F/M Ratio , g BOD_5 Applied/day/g MLVSS	0.09	
Recycle Suspended Solids (No. 1), mg/l	13,310	1242
Recycle Volatile Suspended Solids (No. 1), mg/l	9590	874
Recycle P (No. 1), mg/l	418	70
Recycle Suspended Solids (No. 2), mg/l	11,160	1764
Recycle Volatile Suspended Solids (No. 2), mg/l	8060	1157
Recycle P (No. 2), mg/l	360	90
Recycle VSS % P (No. 1)	4.4	
Recycle VSS % P (No. 2)	4.5	

TABLE 27. INFLUENT AND EFFLUENT CHARACTERISTICS FOR THE NINE PASS REACTOR FROM FEBRUARY 26 TO APRIL 5, 1976

Parameter	Influent		Clarifier No. 1 Effluent		Clarifier No. 2 Effluent	
	Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation
BOD, mg/l	131	16.6	10.9	3.7	11.8	5.1
Inhibited BOD, mg/l	-	-	7.2	3.6	7.8	3.9
COD, mg/l	246	19.5	33.2	11.6	35.0	10.0
SS, mg/l	103	14.2	14.8	7.6	14.7	8.6
VSS, mg/l	81	9.4	9.7	5.3	9.8	5.9
NH_4^+-N, mg/l	12.8	0.91	0.3	0.13	0.3	0.13
$(NO_2^- + NO_3^-)$-N, mg/l	-	-	1.0	0.33	0.9	0.26
Total P, mg/l	5.6	0.75	3.5	0.53	3.5	0.71
Temp., ^oC	17.6	0.6				

period of February 26-April 5, 1976, should have been "typical" and not influenced by the clarifier failure at the end of December.

At an average nitrification rate of 2.5 mg (NO_2^- + NO_3^-)-N/hr/g VSS, MLVSS of 3530 mg/l and an influent flow of 111 l/min (29.4 gpm), one could potentially oxidize 20.3 mg/l of incoming NH_4^+-N prior to the denitrification sequence. Hence system operation during this period was geared to maximizing nitrogen removal through a single nitrification-denitrification cycle. This is, in fact, what occurred and the effluent NH_4^+-N concentration was 0.3 mg/l and the effluent (NO_2^- + NO_3^-)-N concentration was < 1.0 mg/l during the period summarized in Tables 26 and 27.

The P content of the recycle solids was still somewhat higher than normal because of the remaining chemical sludge. The influent mass of phosphorus divided by the effluent plus waste total mass was 1.13 which is a reasonably good balance. Net solids production was 0.46 g SS/g BOD_5 applied and 0.33 g VSS/g BOD applied.

On April 6 the influent flow was increased to a steady rate of 151 l/min (40 gpm). Flow was stable at this level until May 11 when one of the construction crews on the main D.C. plant severed the power supply to the pilot plant and all flows and mixing equipment were off for 27 hours. There was about a 9-day transition period following the flow increase on April 6 in which the effluent NH_4^+-N level was $\sim$ 1.0 mg/l. Process characteristics were generally stable from April 15-May 10 and the response during this 26-day period is summarized in Tables 28 and 29. The loading to the first aerated chambers during this period was high enough to prevent all NH_4^+-N from being oxidized at this point during the part of the day of high NH_4^+-N concentrations. However, the oxidation was essentially completed in the terminally aerated chamber with the result that the effluent (NO_2^-+NO_3^-)-N concentration averaged 1.4 mg/l. No laboratory kinetic studies were conducted during this period. Previous studies indicate the nitrification rate would have been on the order of 3 mg (NO_2^- + NO_3^-)-N/hr/g MLVSS, and at the average solids and flow conditions existing during this portion of the project one could only expect to oxidize a maximum incoming NH_4^+-N concentration of 14.6 mg/l in the first two aerated passes of the reactor.

The loss of power on May 11 effectively terminated a defined transition to steady state operation at the higher loading. Following restoration of the severed power supply on May 12, the influent flow was set at 132 l/min (35 gpm) and the system was operated without further incident at constant flow and waste rates until July 2 when the study was terminated and the system drained. The brief disruption in system operation had no marked impact on subsequent system performance since the effluent quality returned to normal by May 14. The major effort from the 14th to the conclusion of the study was devoted to several laboratory experiments, and the process was simply operated to provide a good quality effluent and serve as a source of biological solids for the laboratory studies. For example, during the last 31 days of operation, the effluent NH_4^+-N averaged 0.1 mg/l with effluent (NO_2^- + NO_3^-)-N concentrations of 1.1 mg/l (Tables 30 and 31).

TABLE 28. PROCESS CHARACTERISTICS FOR THE NINE PASS REACTOR FROM APRIL 15 TO MAY 10, 1976

Parameter	Value or Average	Standard Deviation
Total Reactor Detention Time, hrs	7.1	
Aerated Reactor Detention Time, hrs	2.3	
Influent Flow, gpd	60,600	
Influent Flow, m^3/day	229	
Total Recycle Flow, gpm	19	
Total Recycle Flow, l/min	72	
Clarifier Overflow Rates, gpd/ft^2	390	
Clarifier Overflow Rates, m/day	15.9	
MLSS, mg/l	4080	323
MLVSS, mg/l	3030	251
Total Reactor SRT, days	26	
F/M Ratio, g BOD_5 Applied/day/g MLVSS	0.13	
Recycle Suspended Solids (No. 1), mg/l	12,780	855
Recycle Volatile Suspended Solids (No. 1), mg/l	9390	614
Recycle P (No. 1), mg/l	378	72
Recycle Suspended Solids (No. 2), mg/l	12,590	1,108
Recycle Volatile Suspended Solids (No. 2), mg/l	9,320	848
Recycle P (No. 2), mg/l	380	79
Recycle VSS % P (No. 1)	4.0	
Recycle VSS % P (No. 2)	4.1	

TABLE 29. INFLUENT AND EFFLUENT CHARACTERISTICS FOR THE NINE PASS REACTOR FROM APRIL 15 TO MAY 10, 1976

Parameter	Influent		Clarifier No. 1 Effluent		Clarifier No. 2 Effluent	
	Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation
BOD, mg/l	120	22.0	10.5	3.6	11.3	3.5
Inhibited BOD, mg/l	-		7.3	3.3	8.2	3.5
COD, mg/l	237	31	29.3	7.2	30.5	6.1
SS, mg/l	97	9.0	11.8	7.8	16.1	11.1
VSS, mg/l	76	8.4	7.5	4.1	11.6	7.8
NH_4^+-N, mg/l	12.1	0.57	0.3	.14	0.3	.15
$(NO_2^- + NO_3^-)$-N, mg/l	0	0	1.4	0.44	1.4	0.47
Total P, mg/l	5.1	0.62	3.2	0.34	3.2	0.31
Temp., ^oC	20.6	1.0				

TABLE 30. PROCESS CHARACTERISTICS FOR THE NINE PASS REACTOR FROM JUNE 1 TO JULY 1, 1976

Parameter	Value or Average	Standard Deviation
Total Reactor Detention Time, hrs	8.4	
Aerated Reactor Detention Time, hrs	2.7	
Influent Flow, gpd	51,600	
Influent Flow, m^3/day	195.3	
Total Recycle Flow, gpm	20.5	
Total Recycle Flow, l/min	78	
Clarifier Overflow Rates, gpd/ft^2	331	
Clarifier Overflow Rates, m/day	13.5	
MLSS, mg/l	3200	240
MLVSS, mg/l	2370	180
Total Reactor SRT, days	32	
F/M Ratio, g BOD_5 Applied/day/g MLVSS	0.12	
Recycle Suspended Solids (No. 1), mg/l	9030	534
Recycle Volatile Suspended Solids (No. 1), mg/l	6740	378
Recycle P (No. 1), mg/l	272	35.8
Recycle Suspended Solids (No. 2), mg/l	8460	547
Recycle Volatile Suspended Solids (No. 2), mg/l	6290	394
Recycle P (No. 2), mg/l	241	21.8
Recycle VSS % P (No. 1)	4.0	
Recycle VSS % P (No. 2)	3.8	

TABLE 31. INFLUENT AND EFFLUENT CHARACTERISTICS FOR THE NINE PASS REACTOR FROM JUNE 1 TO JULY 1, 1976

Parameter	Influent		Clarifier No. 1 Effluent		Clarifier No. 2 Effluent	
	Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation
BOD, mg/l	97	14.0	6.5	2.2	7.8	2.1
Inhibited BOD, mg/l	-		3.8	1.6	4.9	1.6
COD, mg/l	210	18.4	21.7	3.8	23.6	3.7
SS, mg/l	81	12.1	7.9	4.5	9.0	4.6
VSS, mg/l	64	10.6	5.4	3.3	6.1	3.6
NH_4^+-N, mg/l	11.4	0.83	0.09	0.03	0.1	0.05
$(NO_2^- + NO_3^-)$-N, mg/l	-		1.1	0.11	1.1	0.12
Total P, mg/l	4.9	0.40	3.4	0.40	3.4	0.29
Temp., ^oC	24.7	1.3				

KINETIC STUDIES

Three similar kinetic studies were preformed during the last 10 days of May according to the following experimental protocol:

(a) Recycle solids were used to partially fill each of two cube containers.

(b) KNO_3 was added to give a desired NO_3^- concentration.

(c) One of the cube containers was filled with recycle solids and the other was filled with primary effluent.

(d) After about 30 seconds of mixing, samples were withdrawn for filtration. The total elapsed time between the addition of NO_3^- and the withdrawal of the first sample was approximately 2 minutes.

(e) Samples for NO_3^- analysis were gravity filtered through Whatman paper.

(f) Samples for COD analyses were vacuum filtered through 984 H Reeve Angel glass fiber filters without the cellulose pads.

The first experiment (Figure 14) established once again the linearity of the denitrification reaction down to very low levels of NO_3^-. A denitrification rate of 6.6 mg $(NO_2^- + NO_3^-)$-N/hr/gm VSS was observed in the unit receiving primary vs. 1.6 mg $(NO_2^- + NO_3^-)$-N/hr g VSS in the control system. The soluble COD in the unit receiving the primary was reduced from 85 mg/l to 50 mg/l within 15 minutes.

A higher NO_3^- concentration was used in the second study (Figures 15 and 16) and the initial denitrification rate in the unit receiving primary effluent was 6.5 mg $(NO_2^- + NO_3^-)$-N/hr/g VSS. The kinetic rate decreased after 24-31 minutes (depending upon what one considers the lines of best fit). The rate associated with the dashed line in Figure 16 is 4.1 mg $(NO_2^- + NO_3^-)$-N/hr/g VSS. The soluble COD removal rate was essentially the same as in the previous experiment with the readily degradable soluble COD being removed in about 20 minutes.

The third study was carried out over a somewhat longer time period (Figures 17 and 18). Three denitrification rates are shown for the system receiving primary effluent. As in the previous study, different curves could also be fit through the data points. Once again, the initial denitrification rate corresponds very well to the other two studies. Similarly the readily degradable soluble COD was removed in about 20 minutes.

The results presented in Figures 16 and 18 are of interest in interpreting the past kinetic studies summarized in Table 1. A typical kinetic study consisted of mixing influent to recycle in a 2:1 ratio, aeration, and then primary addition to simulate 1/4 of the total influent flow being bypassed directly to denitrification. In this case , the additional primary

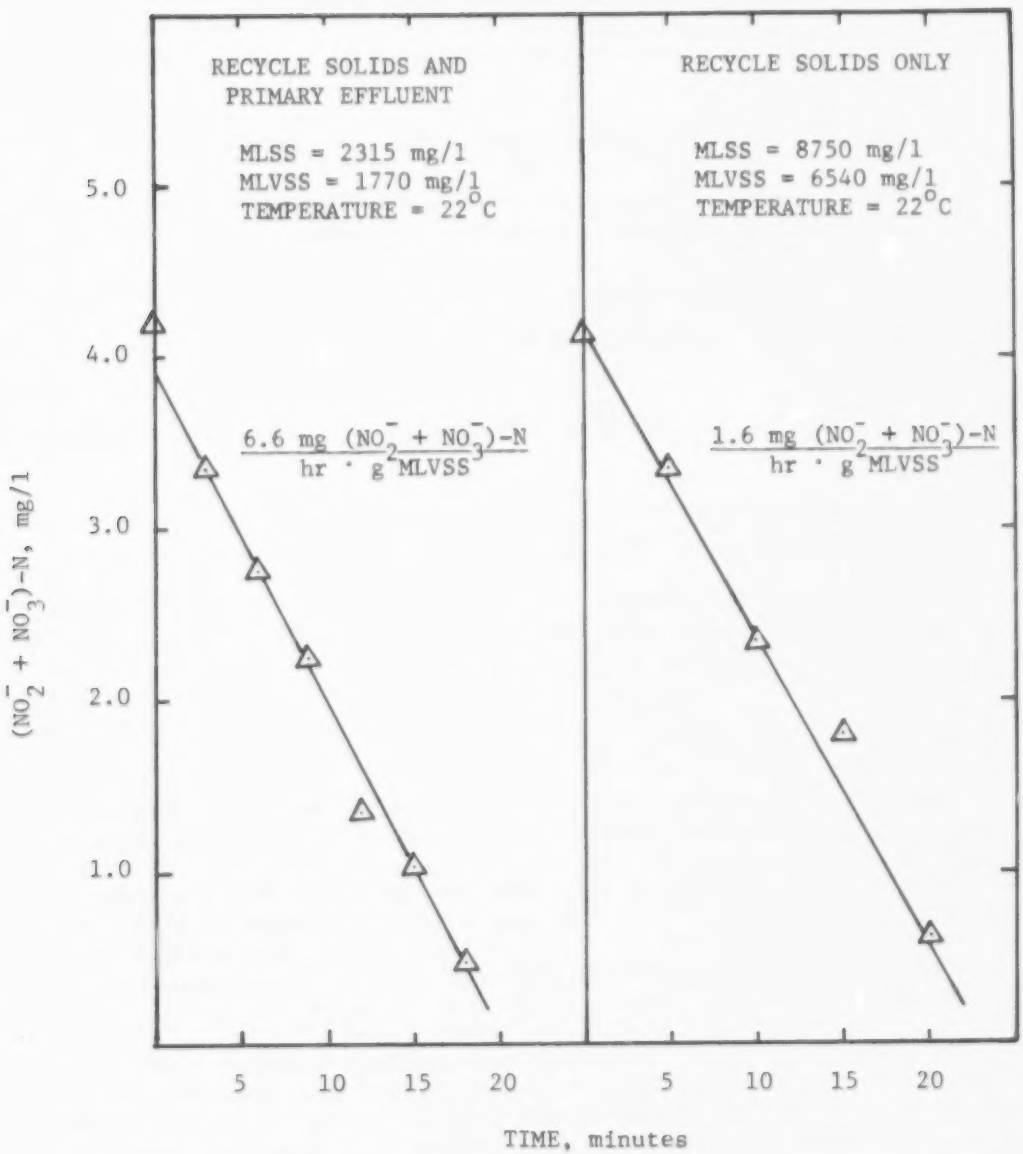

Figure 14. Increase in rate of denitrification with primary effluent addition.

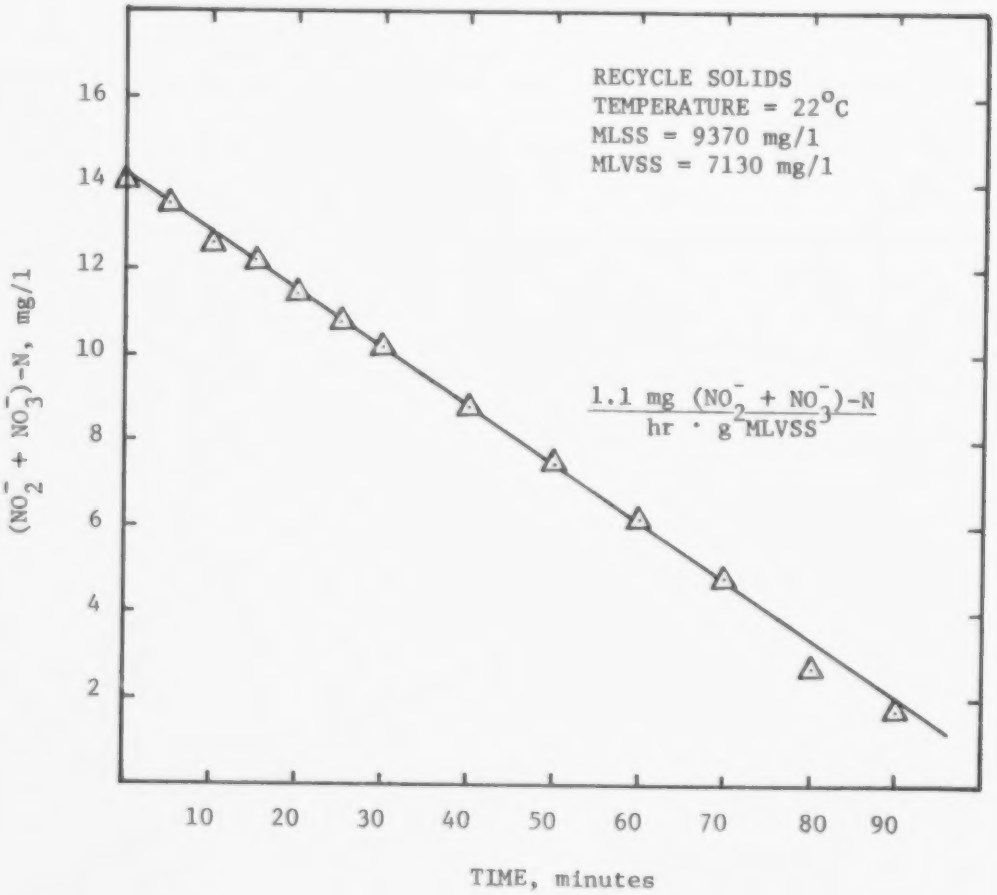

Figure 15. Denitrification kinetic rate with recycle solids on May 25, 1976.

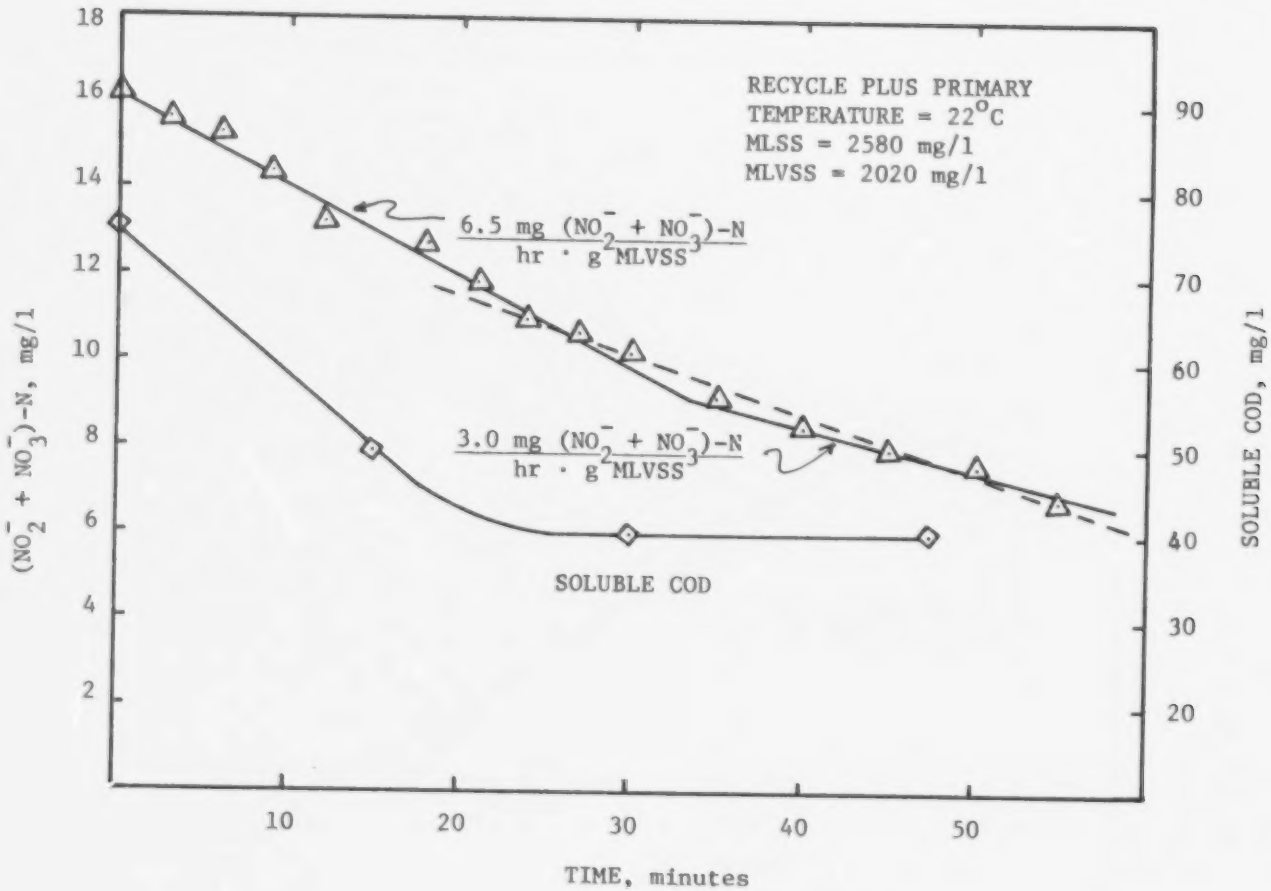

Figure 16. Denitrification kinetic rate with recycle solids and primary effluent on May 25, 1976.

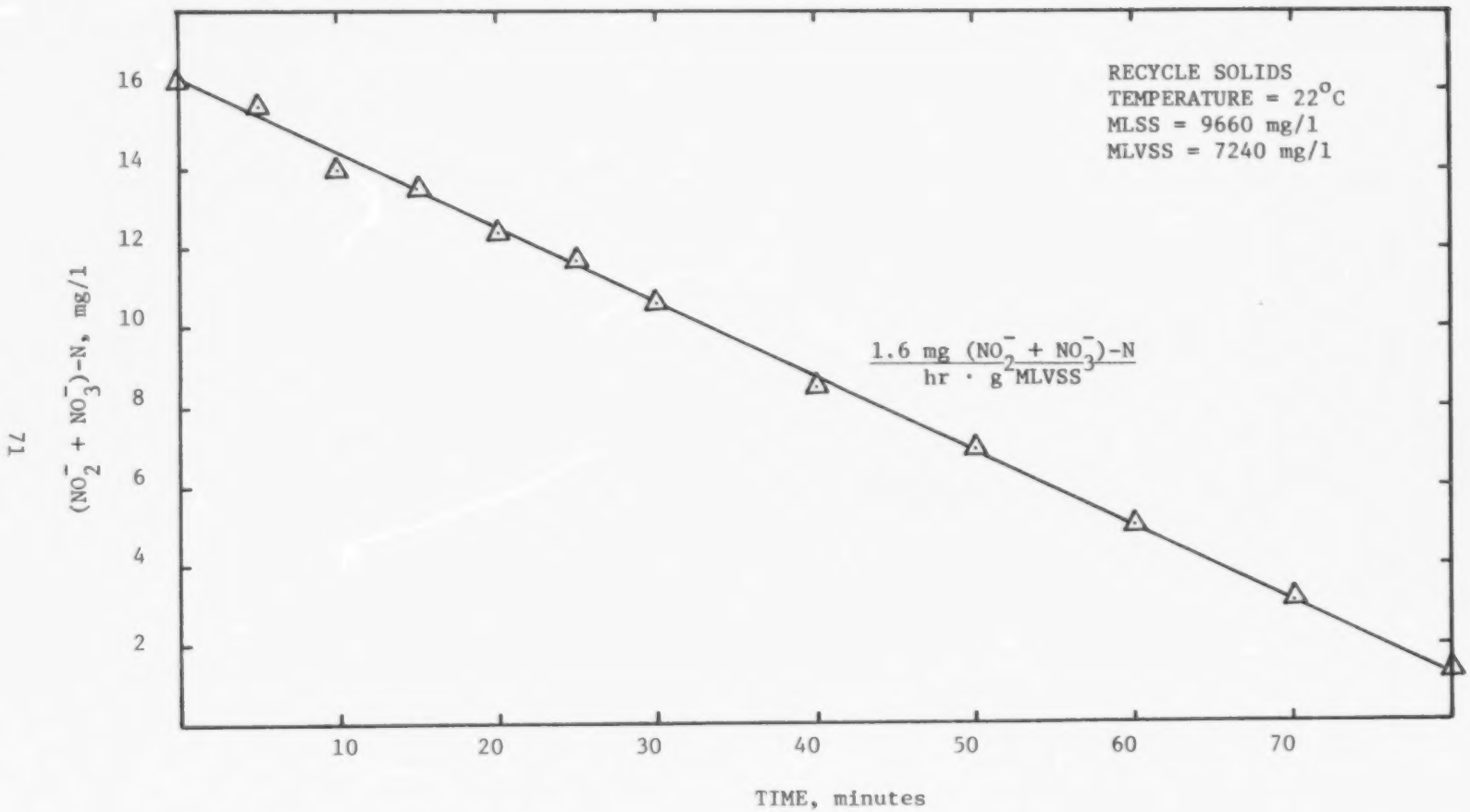

Figure 17. Denitrification kinetic rate with recycle solids on May 28, 1976.

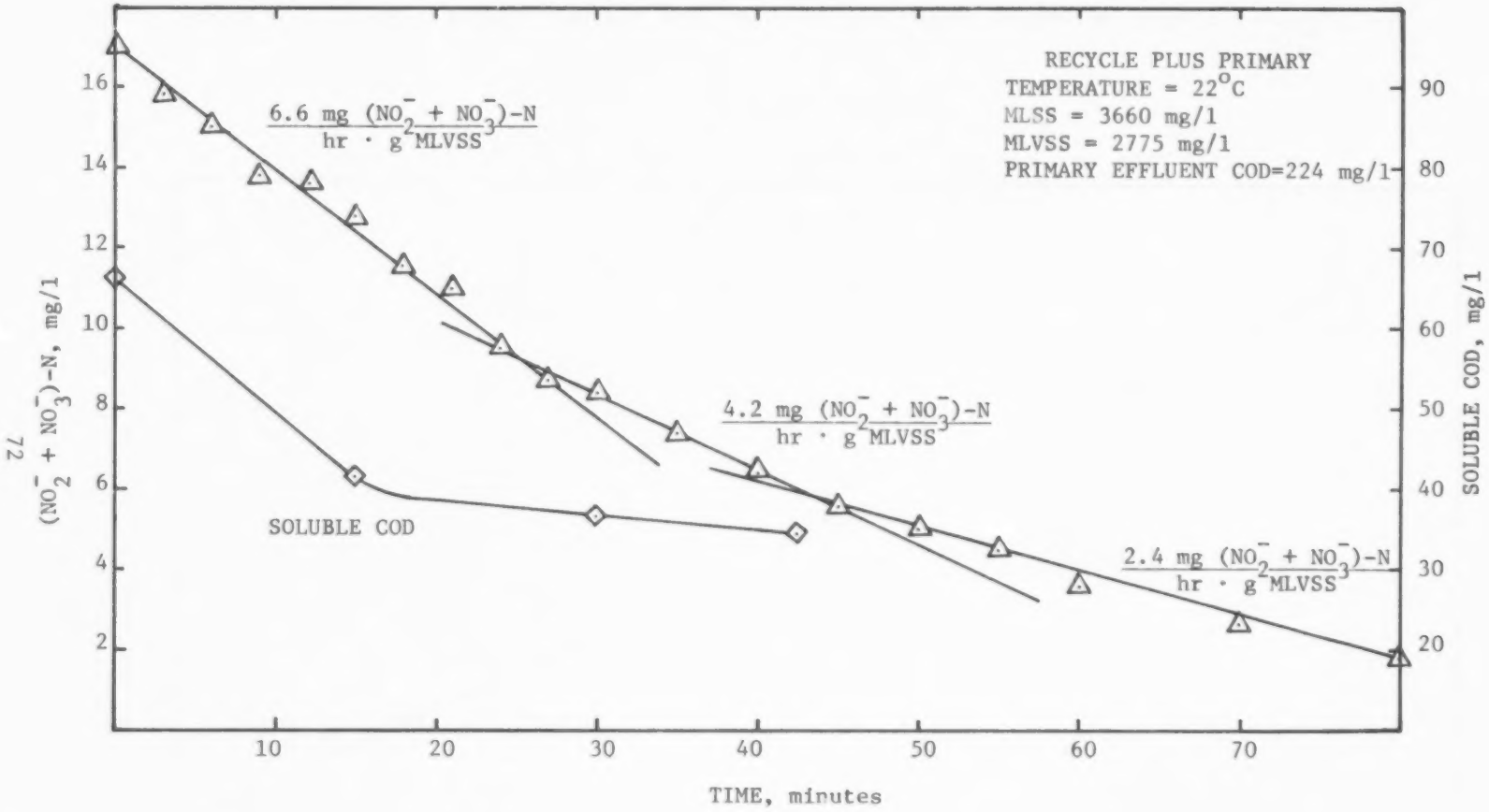

Figure 18. Denitrification kinetic rate with recycle solids and primary effluent on May 28, 1976.

would have increased the readily degradable soluble COD by about 10 mg/1. At the COD removal rates indicated in the three previous kinetic studies, this material would have been removed in approximately 5 minutes. Since the primary was added to an aerated system (2-6 mg/1 residual D.O.) and since 3-4 minutes were required after supplemental primary addition to transfer this material to a cube container, stir and begin collecting samples, any initial high rate during soluble COD removal would only have lasted about 5 minutes and would never have been observed.

Three laboratory studies were conducted on June 10 with the results presented in Figures 19 thru 21. In one case (Figure 19), recycle solids were aerated for 60 minutes, KNO_3 was then added, and the denitrification rate measured. In the second case (Figure 20) recycle solids were mixed with primary effluent, aerated for 60 minutes, and then the denitrification rate was measured. In the third case (Figure 21) filtered primary effluent was added. The denitrification rates were 1.2, 2.1 and 1.7 mg N/hr/g VSS, respectively. The soluble COD removal rates were the same, within experimental error, in units receiving primary or filtered primary. Although the degradable soluble COD was removed in the third unit well before the end of the aeration period, the endogenous denitrification rate was enhanced over that observed in the control unit but not to the extent observed in the unit receiving unfiltered primary. It is apparent that the colloidal material in the unfiltered primary (an extra 90 mg/1 as COD) did not influence the denitrification rate beyond what could be attributed simply to more initial COD.

In a study on the following day, filtered and unfiltered primary effluent and KNO_3 were added to recycle solids and the denitrification rates were measured. Results are presented in Figure 22. Once again the soluble COD was removed very rapidly. The initial denitrification rates of 7.0 and 7.2 mg N/hr/g VSS were the same within experimental error. The subsequent denitrification rates were only marginally higher in the unit receiving unfiltered primary indicating that the extra 95 mg/1 of particulate COD was apparently being degraded rather slowly.

On June 24 two studies were conducted in which recycle solids were added to primary effluent and then aerated until nitrification was complete (Figures 23 and 24). Concurrent measurement of soluble COD removal showed that the degradable component of the material was removed in less time than was required to completely oxidize the NH_4^+-N. This same observation was essentially made when the actual process was sampled several days later; results of NH_4^+-N, $(NO_2^-+NO_3^-)$-N, and COD analyses are presented in Table 32. It can be seen that nitrification was essentially complete in the first pass and the soluble COD was also reduced to its residual level by this point. An accurate determination of the nitrification kinetic rate is not possible from these data as the NH_4^+-N oxidation rate is not zero order when the concentration is below 1 mg/1. The average $(NO_2^-+NO_3^-)$-N reduction from passes 3 to 4 and 4 to 5 corresponds to a denitrification kinetic rate of 1.55 mg $(NO_2^-+NO_3^-)$-N/hr/g VSS. This rate agrees well with denitrification rates obtained in the various batch kinetic tests.

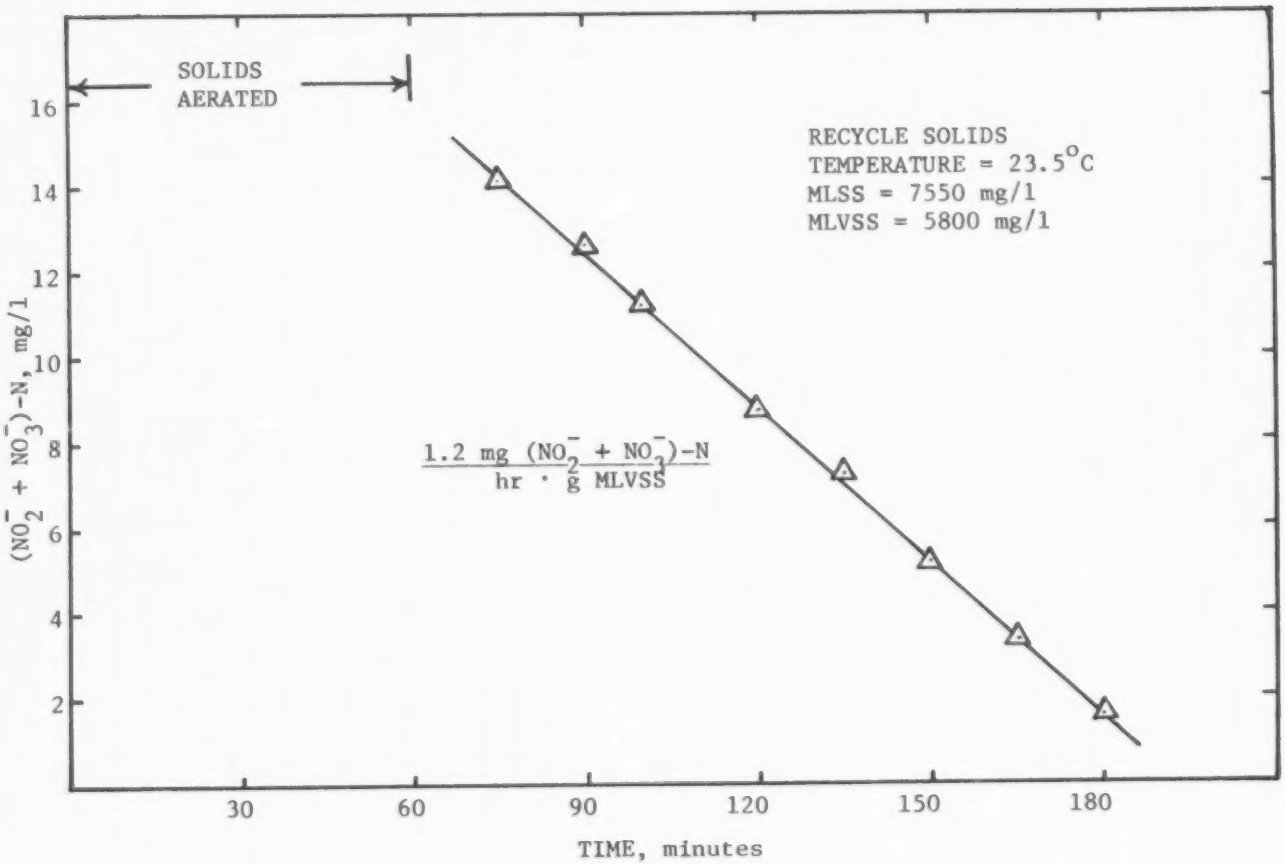

Figure 19. Denitrification kinetic rate with recycle solids after 60 minute's aeration on June 10, 1976.

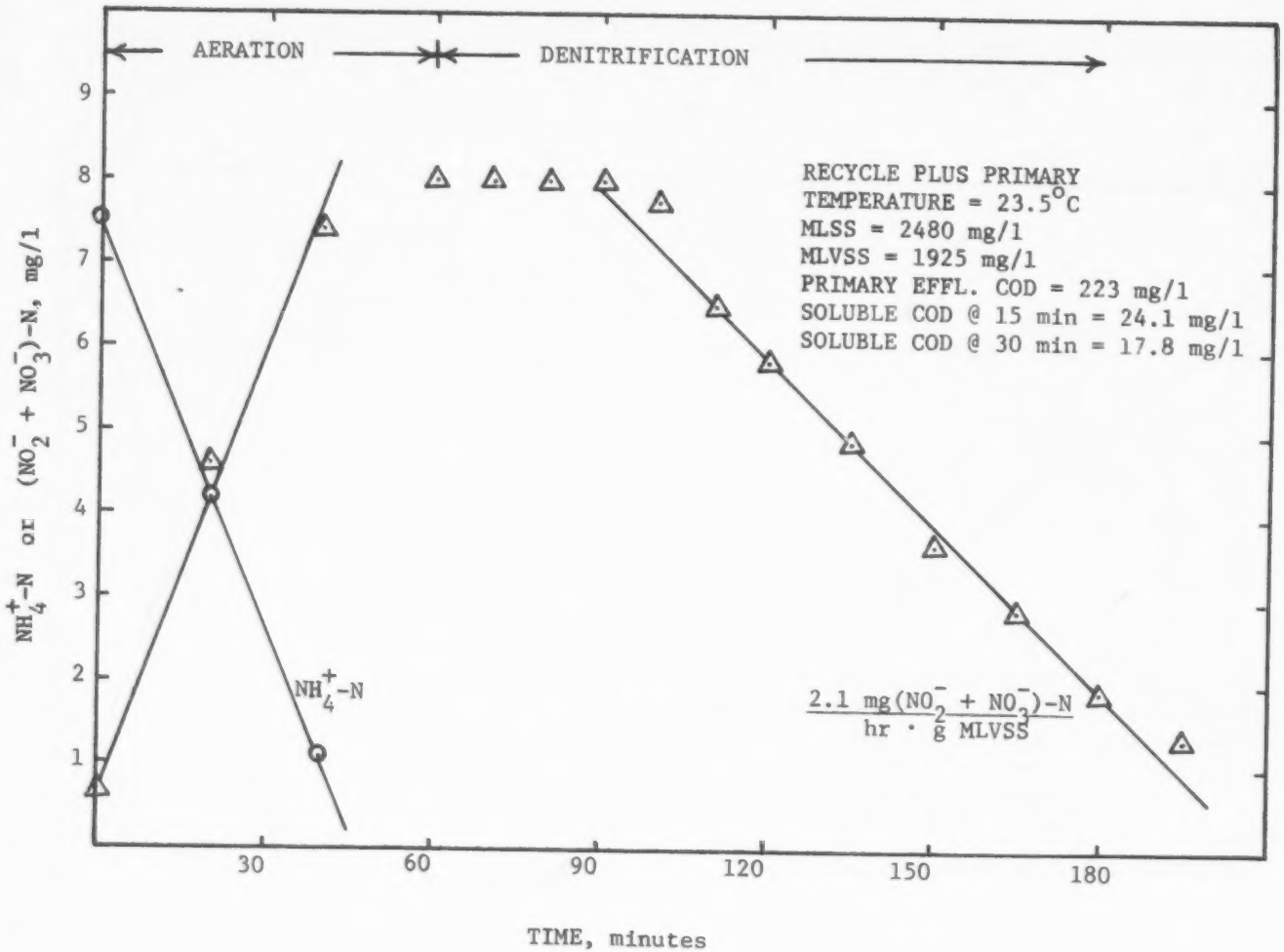

Figure 20. Nitrification-Denitrification cycle with recycle solids and primary effluent on June 10, 1976.

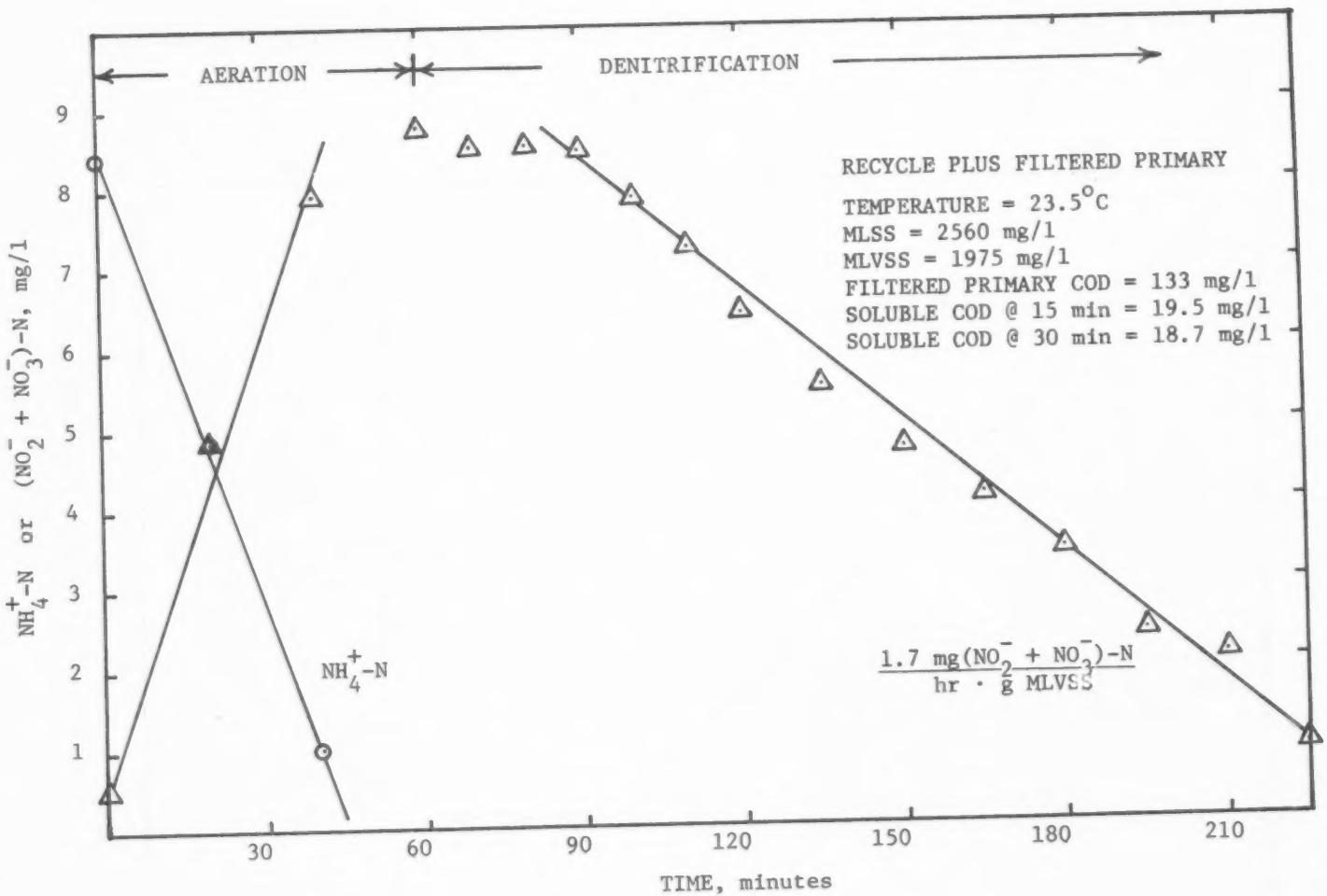

Figure 21. Nitrification-Denitrification cycle with recycle solids and filtered primary effluent on June 10, 1976.

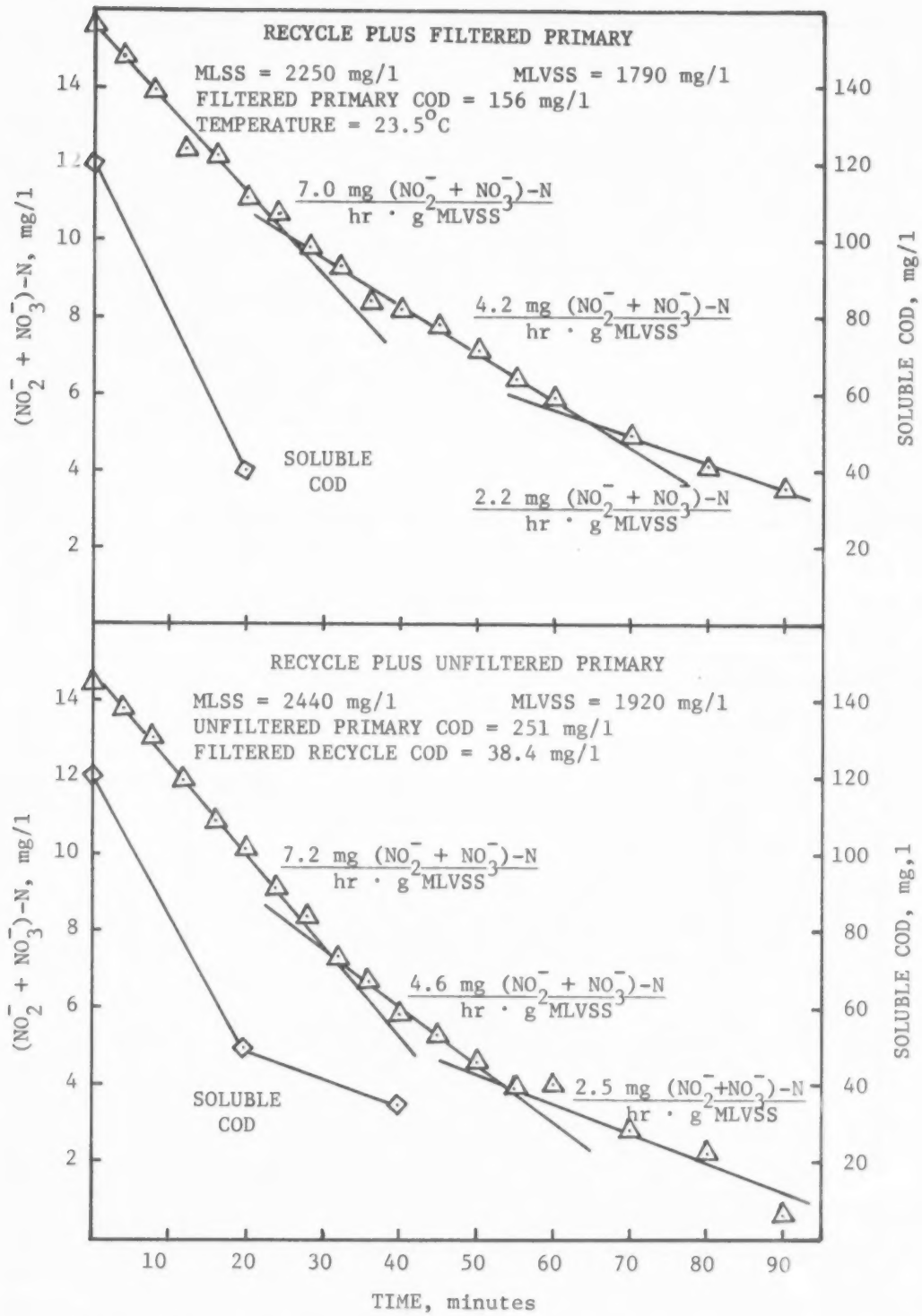
RECYCLE PLUS FILTERED PRIMARY
MLSS = 2250 mg/l
MLVSS = 1790 mg/l
FILTERED PRIMARY COD = 156 mg/l
TEMPERATURE = 23.5°C
7.0 mg (NO2- + NO3-)-N / hr · g MLVSS
4.2 mg (NO2- + NO3-)-N / hr · g MLVSS
2.2 mg (NO2- + NO3-)-N / hr · g MLVSS
SOLUBLE COD
RECYCLE PLUS UNFILTERED PRIMARY
MLSS = 2440 mg/l
MLVSS = 1920 mg/l
UNFILTERED PRIMARY COD = 251 mg/l
FILTERED RECYCLE COD = 38.4 mg/l
7.2 mg (NO2- + NO3-)-N / hr · g MLVSS
4.6 mg (NO2- + NO3-)-N / hr · g MLVSS
2.5 mg (NO2-+NO3-)-N / hr · g MLVSS
SOLUBLE COD
(NO2- + NO3-)-N, mg/l
SOLUBLE COD, mg/l
TIME, minutes

Figure 22. Comparison of denitrification rates using filtered and unfiltered primary effluent.

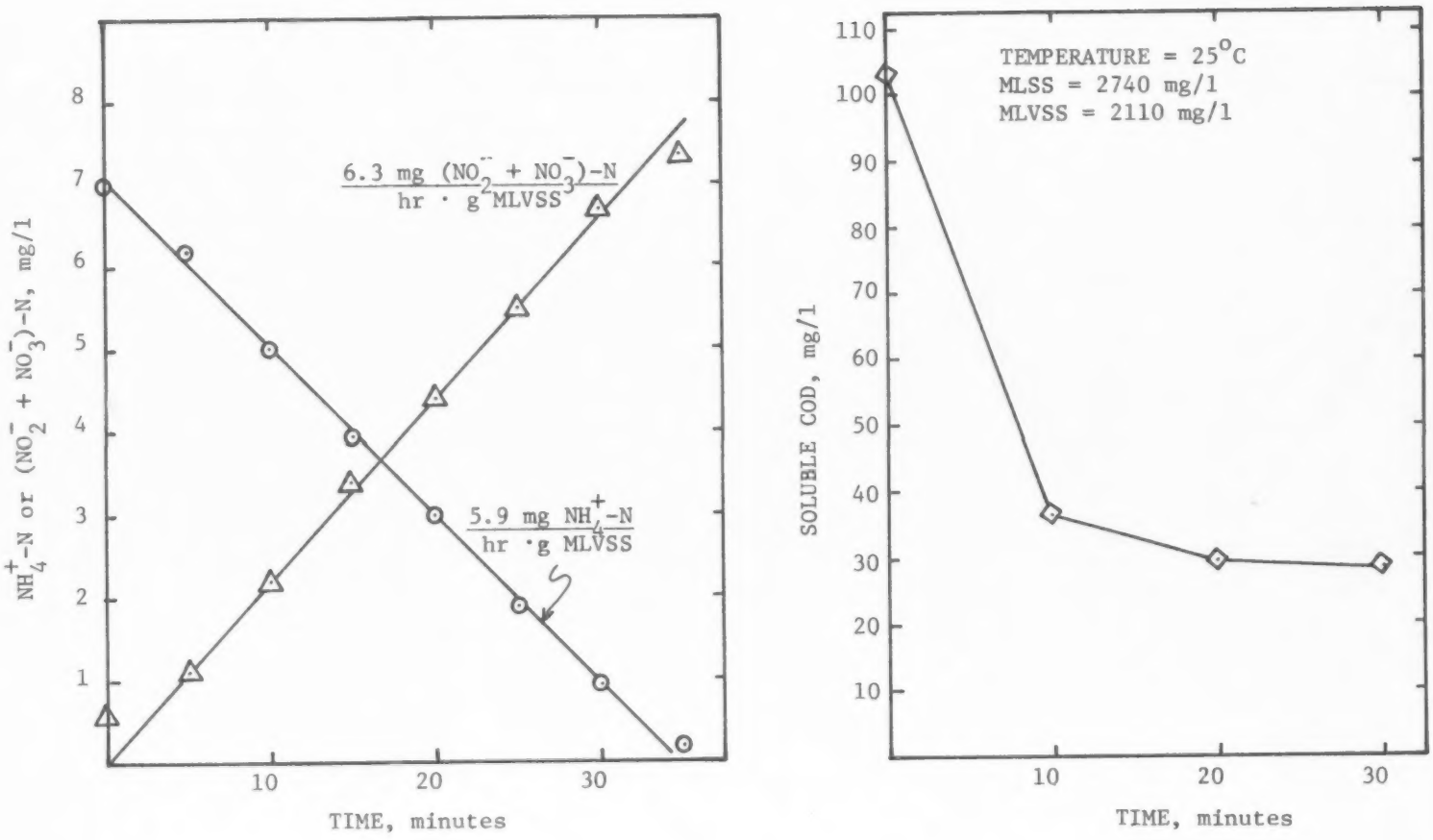
6.3 mg (NO2- + NO3-)-N / hr · g MLVSS
5.9 mg NH4+-N / hr · g MLVSS
NH4+-N or (NO2- + NO3-)-N, mg/l
TIME, minutes
TEMPERATURE = 25°C
MLSS = 2740 mg/l
MLVSS = 2110 mg/l
SOLUBLE COD, mg/l
TIME, minutes

Figure 23. Comparison of soluble COD removal rate and the time required for nitrification (Test No. 1).

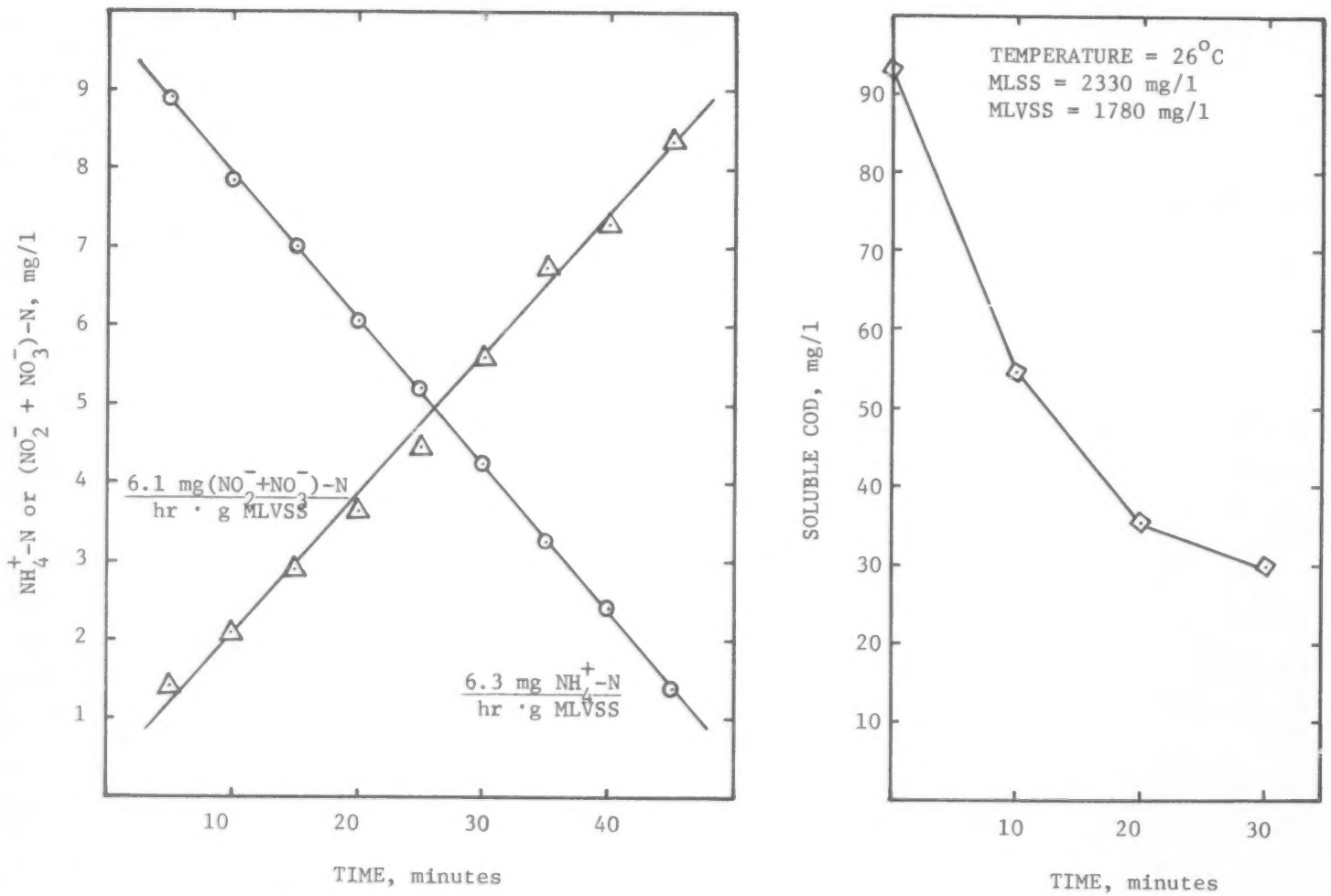
TEMPERATURE = 26°C
MLSS = 2330 mg/l
MLVSS = 1780 mg/l
SOLUBLE COD, mg/l
TIME, minutes
NH_4^+-N or (NO_2^- + NO_3^-)-N, mg/l
6.1 mg(NO_2^-+NO_3^-)-N / hr · g MLVSS
6.3 mg NH_4^+-N / hr · g MLVSS
TIME, minutes

Figure 24. Comparison of soluble COD removal rate and the time required for nitrification (Test No. 2).

TABLE 32. NH_4^+-N, (NO_2^- + NO_3^-)-N AND COD CONCENTRATIONS IN THE NINE PASS REACTOR AT SELECTED TIMES ON JULY 1, 1976 *

Time	Influent	Pass 1	Pass 2	Pass 3	Pass 4	Pass 5	Pass 6	Pass 7	Pass 8
					NH_4^+ - N, mg/l				
1230	9.9	0.1	0.2	0.2	1.1	0.7	1.1	1.1	1.1
1350	12.8	0.6	-	-	-	-	-	-	1.1
1530	13.9	0.9	-	-	-	-	-	-	0.9
					(NO_2^- + NO_3^-)-N				
1230		6.6	6.9	6.8	4.6	2.3	1.3	0.8	0.7
1350		7.0	7.0	7.4	4.7	2.4	0.9	-	0.8
1530		8.1	8.4	8.2	6.0	3.4	1.3	0.8	1.2
					Soluble COD, mg/l				
1350	-	22.4	23.9	(	R e c y c l e =	1 9 . 7	)		
1420	104	-	-						
1530	95.8	20.8	18.5						

*Process Temperature = 27°C
*Average MLSS = 3,230 mg/l
*Average MLVSS = 2,470 mg/l
*Recycle Flow = 78.0 l/min (20.6 gpm)
*Influent Flow = 127.2 l/min (33.6 gpm)
*Detention Time per Pass Based on Total Flow = 37.4 min

The effects of overaeration were evaluated on June 25 (Table 5) when a mixture of recycle and influent was aerated until nitrification was complete. Part of the mixture was then allowed to denitrify immediately with the remainder aerated an additional 60 minutes prior to denitrification. The overaeration resulted in a denitrification rate of 1.0 mg $(NO_2^- + NO_3^-)$-N/hr/g VSS compared to a rate of 1.3 in the sample that was denitrified at the end of the nitrification cycle.

In the last kinetic test performed, a sample was nitrified, split into two parts, and 33% additional primary added to one of the two parts prior to denitrification (Table 1). As previously observed over the last 1-1/2 years, the increased denitrification rate resulting from the additional primary addition was not sufficiently large to justify a more complex flow-splitting scheme. COD values were: primary effluent, 244 mg/l; soluble primary, 138 mg/l; soluble recycle, 42.8 mg/l; soluble component after 20 and 30 minutes aeration, 39.0 and 32.3 mg/l, respectively.

SLUDGE SETTLING CHARACTERISTICS

Throughout the course of this investigation, the mixed liquor from the last aerated reactor pass was periodically removed and the settling velocity determined in the stirred .15 m (6") column previously described. These velocities are summarized in Table 33. The results appear generally typical of other single stage systems. Nocardia is a filamentous organism and this is reflected in the low settling velocities encountered especially at low temperatures and high solids. The $FeCl_3$ addition increased the settling velocities compared to a system at similar MLSS levels, but obviously this came at the expense of having to maintain higher MLSS because of the lower percentage of volatile solids. On balance these two factors tended to be offsetting.

Two batch flux settling tests were run and the results are shown in Figure 25. The higher settling velocities in December primarily reflect the $FeCl_3$. When these tests were conducted, a subsample was placed in a 1-liter unstirred cylinder for determination of the 30-minute sludge volume. This was used in conjunction with the suspended solids data from each test to compute the SVI as shown in Figure 26. This response is rather typical where filamentous organisms are present and shows that one can attain a range of SVI values depending upon the suspended solids level.

TABLE 33. SUMMARY OF MIXED LIQUOR SETTLING VELOCITIES FROM THE LAST PASS OF THE EIGHT OR NINE PASS REACTOR

Date	Temp °C	MLSS mg/l	Settling Velocity ft/hr	Settling Velocity m/hr	Volatile Solids %	Date	Temp °C	MLSS mg/l	Settling Velocity ft/hr	Settling Velocity m/hr	Volatile Solids %
2/11/75	17	3800	5.3	1.6	70	8/28/75	27	2200	16	4.9	67
2/21/75	17.5	3700	4.3	1.3	70	9/11/75	24.5	2900	11.3	3.4	67
3/6/75	18	3700	6.5	2.0	70	9/18/75	24.5	2600	10.2	3.1	69
3/11/75	17	3400	5.3	1.6	71	9/30/75	23	2800	4.2	1.3	55
3/20/75	16	4100	2.7	0.82	68	10/07/75	23	4200	4.0	1.2	54
3/25/75	17	4000	3.3	1.0	67	10/22/75	22	5200	3.9	1.2	52
4/01/75	18	4200	3.5	1.1	67	10/31/75	22	5500	3.7	1.1	53
4/8/75	17.5	4300	3.3	1.0	68	11/20/75	21	6100	2.6	0.79	55
4/15/75	18	4500	3.1	0.94	70	11/24/75	20	6400	3.1	0.94	56
4/25/75	18.5	4700	1.7	0.52	71	12/16/75	18.5	4700	4.5	1.4	62
5/06/75	19	3900	1.9	0.58	71	12/24/75	17	4900	4.2	1.3	67
5/13/75	21	3800	2.5	0.76	68	1/27/76	16	5100	3.6	1.1	69
5/20/75	22	4000	3.2	0.98	70	2/10/76	16	5800	3.5	1.1	69
5/27/75	23.5	4100	3.9	1.2	69	2/19/76	18	5700	3.1	0.94	70
6/20/75	26	4000	3.8	1.2	68	3/01/76	18.5	5200	3.9	1.2	70
6/26/75	25.5	3700	4.5	1.4	69	3/08/76	18.5	5100	3.9	1.2	72
7/08/75	26	3200	4.8	1.5	70	3/15/76	18.5	4900	4.5	1.4	72
7/14/75	24	3500	4.0	1.2	69	3/29/76	19	4200	9.8	3.0	73
7/22/75	26	3500	6.0	1.8	66	4/06/76	18	3600	6.2	1.9	72
7/31/75	27.5	3100	6.6	2.0	66	5/24/76	22	3700	7.7	2.3	73
8/12/75	27	2500	9.1	2.8	67	6/10/76	24.5	3200	6.5	2.0	76
8/22/75	27	2000	16	4.9	67	6/30/76	26	3000	7.2	2.2	73

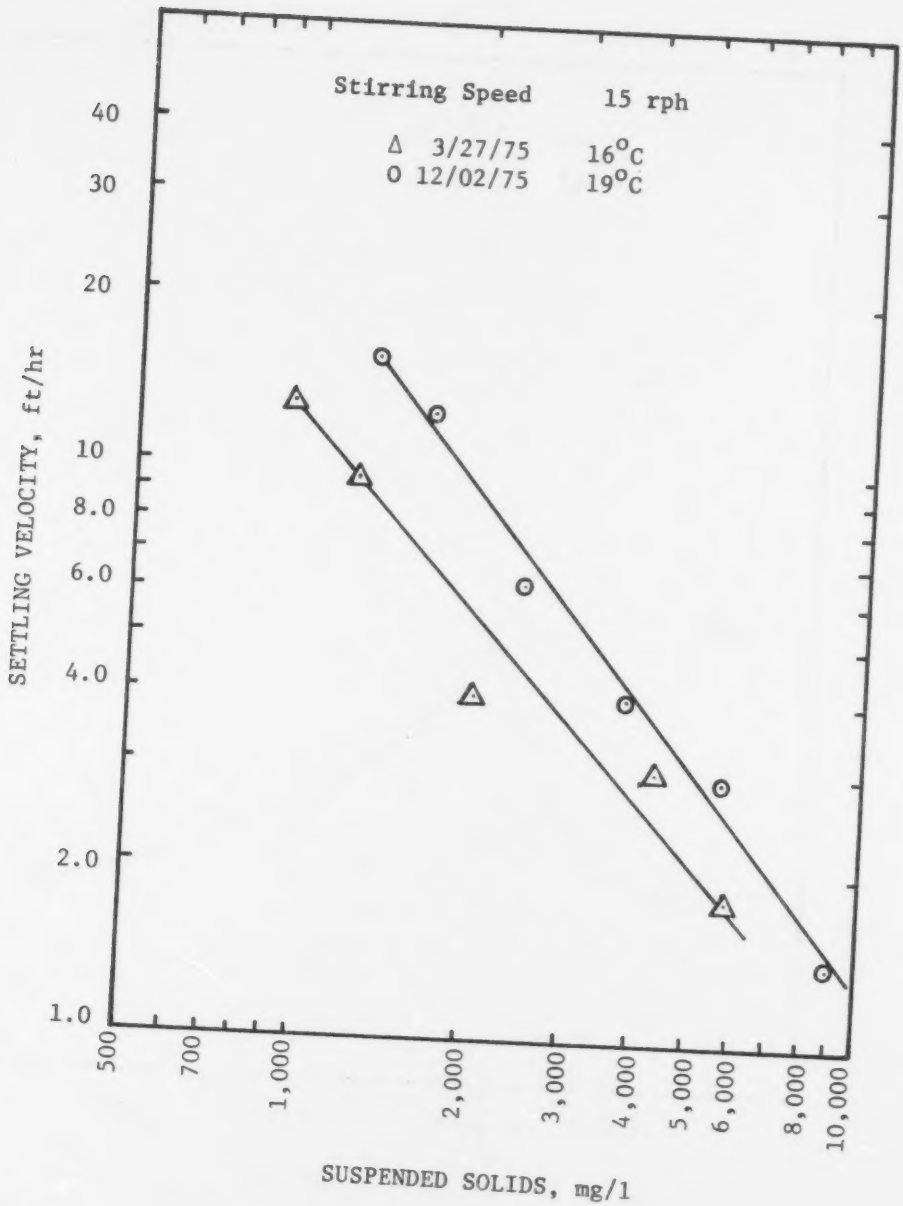

Figure 25. Mixed liquor settling velocity vs. suspended solids concentration.

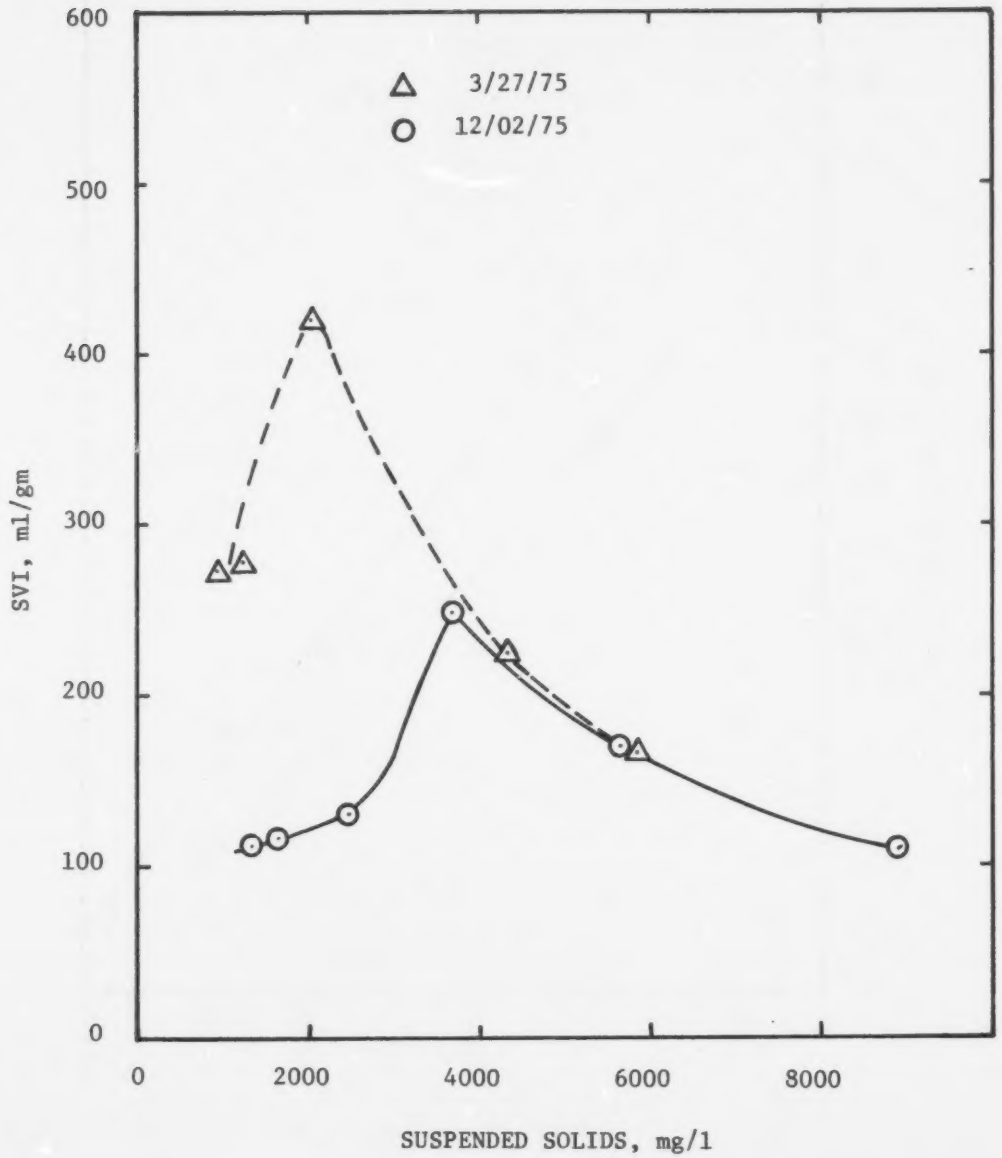

Figure 26. SVI vs. suspended solids concentration.

SECTION 7

DISCUSSION

Based on the results presented in the previous section, it can be seen that acceptable nitrification-denitrification performance was routinely achieved with the nine pass reactor. For many of the steady state periods summarized, the effluent NH_4^+-N was < 0.5 mg/1 and the effluent $(NO_2^- + NO_3^-)$-N concentration was ∿ 1 mg/1. Occasional checks for NO_2^--N were always negative indicating that the measured $(NO_2^- + NO_3^-)$-N was essentially all NO_3^--N. This was the expected result since for the set of conditions prevailing in these studies the Nitrosomonas kinetics essentially control the nitrification response. The overall process response was the result of a number of interacting variables. In fact, there are so many variables that it is impossible to disaggregate the data to a level where the influence of each factor can be examined individually.

The decision to use primary effluent in place of raw sewage provided a lower C:N ratio to the system than would have prevailed without use of a primary clarifier. The BOD:TKN ratio from June-September 1975 was 5:1. Because of reduced laboratory staffing, the TKN analyses were discontinued after September. However, the 5:1 ratio should be representative of that prevailing after September 1975. This value was sufficiently high to exceed the critical ratio required for denitrification (5).

The soluble COD measurements made during the initial aeration periods of some of the laboratory kinetic studies show that the readily degradable soluble material was essentially removed in every case prior to the minimum time required for complete nitrification. If raw sewage and not primary effluent had been applied to the single-stage system, this presumably would have happened even faster because of an increased heterotrophic:nitrifying organism ratio. Since perhaps 50% of the BOD in primary effluent is colloidal or larger in size, this material cannot be metabolized as rapidly as the "soluble" material and would be expected to provide some contribution to "endogenous denitrification." Clearly the use of raw sewage in place of primary would provide even larger amounts of particulate material (∿ 30% BOD removal is common for a primary settler) available for slower degradation. Intuitively, one would expect different denitrification rates with the single nitrification-denitrification approach using raw instead of primary sewage because of the increase in essentially all particulate matter.

The two kinetic studies summarized in Figures 19 thru 22 are somewhat conflicting in their interpretation. The increase in the denitrification rate of 0.5 mg/1/hr in the unit receiving the filtered primary (COD=133 mg/1)

and the increased rate of 0.9 mg/1/hr in the unit receiving the unfiltered primary (COD=223 mg/1) over the rate prevailing in the control unit (Figure 19) indicates no need to differentiate the potential influence of different carbonaceous molecular sizes on the subsequent denitrification rates. On the other hand, the results shown in Figure 22 imply that the colloidal fraction is not used very rapidly and may be quite important in the "endogenous denitrification." This is an area where further studies are needed.

The denitrification rate observed when using a single nitrification-denitrification cycle was obviously very dependent on the length of the initial aeration period as shown in Table 5 and Figure 7. Aeration beyond the minimum time needed to accomplish nitrification clearly reduced the subsequent denitrification rate. The results shown in Table 5 for 9/10, 10/2, and 2/26, indicate that the decline in the denitrification rate is not a simple function of the length of the aeration period. The decline in the denitrification rate with extended aeration is significant enough that one would need to have a uniform length of aeration period to provide a meaningful direct comparison of denitrification rates of the type shown in Table 1.

Since the denitrification rates are a function of the initial COD, the length of the aeration period, temperature, and presumably the soluble: particulate organics ratio, one must exercise considerable caution in interpreting denitrification rates and comparing them to the results of others. When the denitrification rates in Table 1 from 1/22/75 onward for the units receiving no additional primary, the rates from the shortest aeration times in Table 5, and the rate from Figure 20 are plotted as a function of temperature, as shown in Figure 27, there is no obvious relationship. The rates of 0.8 to 2.0 mg $(NO_2^- + NO_3^-)$-N/hr/gm MLVSS are quite consistent with the rates summarized by Christensen and Harremoes (5) for various nitrification-denitrification processes. In view of the variability in aeration times, temperatures, and initial COD values used in the laboratory studies to determine the denitrification rates, it is not possible to define the denitrification rates as a function of each of these variables on the basis of the data at hand.

The maximum denitrification rates observed by mixing primary effluent and recycle solids and then adding KNO_3 were 6.5-7.2 mg $(NO_2^- + NO_3^-)$-N/hr/gm MLVSS, and these rates prevailed only as long as there was a readily available exogenous supply of soluble COD. These rates exceed the 2-3 mg N/hr/gm VSS upper limit indicated by Christensen and Harremoes (5). However, it is obvious that special care must be taken to find this initial rapid rate. Barnard (18) reported a very rapid initial rate lasting from 5 to 15 minutes of 13 mg NO_3^--N/hr/g SS. This was attributed to the reduced state of the anaerobic raw sewage. This rapid rate was not observed here, but it should be noted that the primary influent is pumped from an aerated grit chamber so the same conditions did not prevail. The intermediate denitrification rates of $\sim$ 3.5 mg NO_3^--N/hr/g MLSS described by Barnard agree very well with the rates observed here.

The nitrification kinetic rates with solids from the 8 or 9 pass system are also plotted as a function of temperature in Figure 27. Here the relationship between kinetic rate and temperature is more obvious. However, a

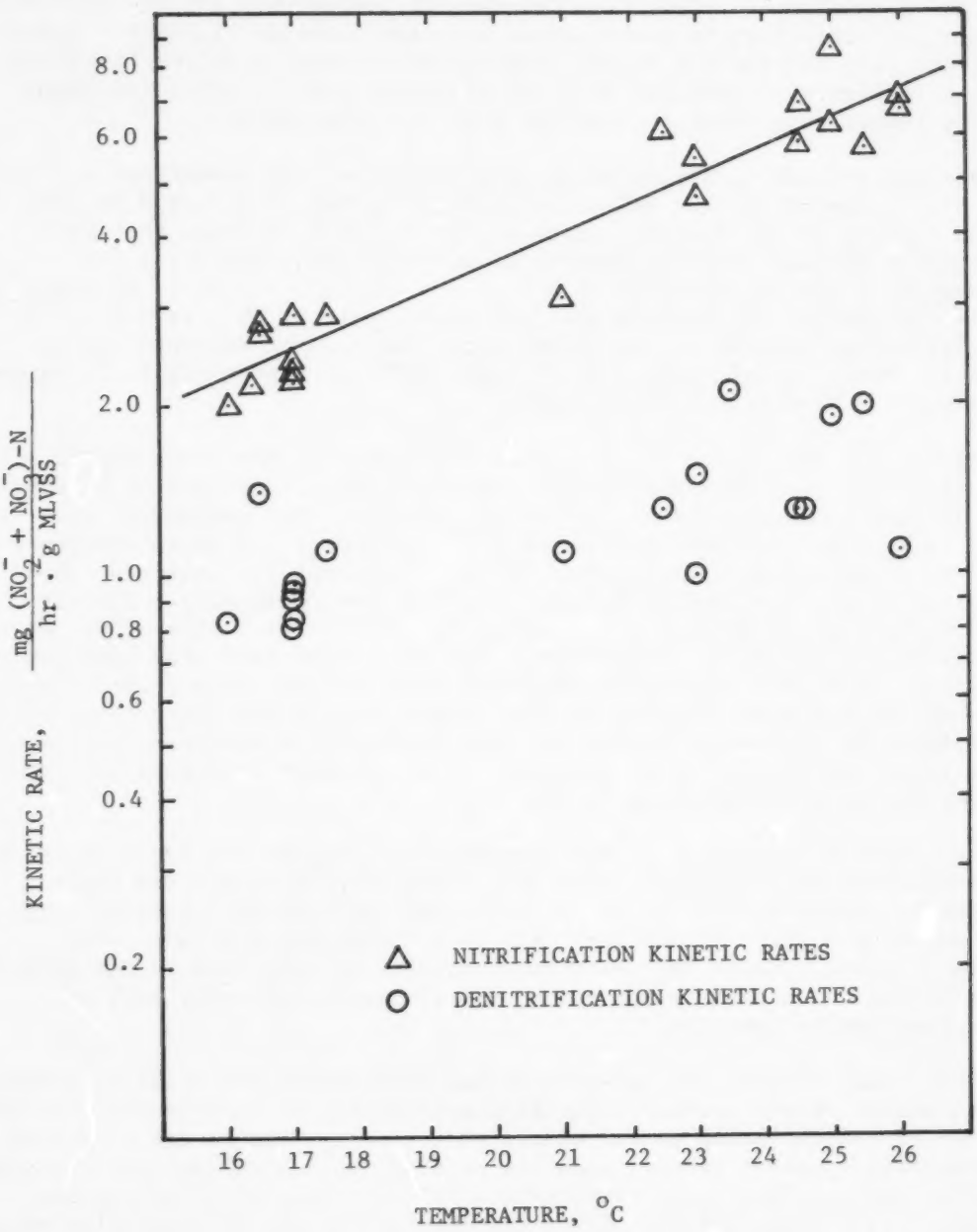

Figure 27. Nitrification and denitrification kinetic rates from laboratory studies vs. temperature.

major problem in data interpretation is that the nitrification rate is basically expressed in terms of the non-nitrifying mass of heterotrophic organisms. Since net heterotrophic yield is a function of temperature (19,20) and SRT, the ratio of nitrifying to carbonaceous organism observed yields may change during the year and imply a larger temperature function than really exists. The data in Figure 27 indicate a 3-fold change in the nitrification rates with the temperature range encountered with D.C. wastewater.

Various periods of steady state operation have been summarized in Table 34. A 30-day reactor SRT corresponds to an SRT of 9.8 days in the aerated portion of the reactor. Knowles, et al. (21) proposed that the relationship between maximum specific growth rate and temperature for Nitrosomonas could be expressed as $\log_{10}\mu = 0.0413\ (T) - 0.944$. According to this expression, the maximum specific growth rate at 15°C is 0.47 days^{-1}. Since SRT is the inverse of the growth rate, the minimum SRT required is 2.1 days. Hence at all times, the "aerated SRT" was substantially in excess of the minimum theoretical value needed.

Except for the period of July 11 to September 22, the other steady state operating periods summarized in Table 34 are only equivalent to about 1 SRT in length. During winter operation, the clarifier bed levels also tended to be high such that the "total SRT" of reactor and clarifier could have been perhaps double the reactor SRT's. This must be considered when evaluating observed sludge production as a function of loading. Clearly the short periods of operation summarized in Table 34 ($\sim$ 1 SRT) offer the possibility of estimating sludge production values far from true equilibrium conditions. This was previously mentioned when the data from 5/28-7/9 were discussed and was also the case for the period of 2/26-4/5 where there were declining MLVSS levels and presumably some wasting from storage. The change was so great for the period of September 23 to December 2 (Figure 13), that this period was not summarized in Table 34.

The overall cell yield coefficient when treating DC primary effluent has been previously estimated (16) at 0.79 g VSS/g BOD_5 applied. The decay coefficient was 0.064 day^{-1}. For a 30-day SRT the expected observed cell yield would be 0.79/[1 +0.064(30)] or 0.27 g VSS/g BOD_5 applied. This assumes a 30-day aerated SRT which was obviously not the case in the present investigation. Nonetheless the value of 0.27 agrees favorably with the values reported in Table 34.

The P mass balance was never unity and this presumably reflects either overestimation of the average influent concentration or an underestimate of the average concentration in the clarified effluent. The sludge P content was generally constant (where there was no $FeCl_3$ influence) and the recorded underflow waste volumes gave observed cell yield values which were quite consistent with expectations. Since the accuracy of the influent flow meter was checked weekly, the estimate of influent flow for all periods of steady flow should not be in error by more than 3-4%. The method of underflow wasting also makes it extremely unlikely that the waste volumes were not measured correctly to within 10% and in all probability the error was no more than 5%.

TABLE 34. SUMMARY OF OBSERVED CELL YIELDS, F/M RATIOS AND PROCESS SRT'S FOR SELECTED PERIODS

Dates	Number of Days	Average Temp °C	SRT days	Observed Yield		F/M	P
				$\frac{g\ SS/day}{g\ BOD_5\ Appl.}$	$\frac{g\ VSS/day}{g\ BOD_5\ Appl.}$	$\frac{g\ BOD_5\ Appl.}{day\ .\ g\ MLVSS}$	Mass Balance In/Out
5/28-7/9	43	24.5	28	0.58	0.40	0.09	1.12
7/11-9/22	74	26.2	35	0.37	0.25	0.12	1.41
11/1-12/2	32	20.8	27	-	0.43	0.09	-
12/4-12/23	20	18.2	20	-	0.48	0.10	-
2/26-4/5	40	17.6	35	0.46	0.33	0.09	1.13
4/15-5/10	26	20.6	26	0.40	0.29	0.13	1.21
6/1-7/1	31	24.7	32	0.37	0.27	0.12	1.17

If one has a perfect N balance, it is possible to take the $TKN_{in} - TKN_{out} - (NO_2 + NO_3)\text{-}N_{out}$ and calculate the nitrogen removal resulting from the nitrification-denitrification cycle plus whatever nitrogen removal occurs through denitrification in the final clarifier. The loss in the clarifier can be significant especially with high clarifier bed levels. When this calculation was applied to the system parameters for the period of 5/28 to 7/9, it was determined that 12.9 mg/l of the incoming 18 mg/l of nitrogen were removed in the nitrification-denitrification process. Of the remainder, 2.2 mg/l of N passed into the effluent and the equivalent of 2.9 mg/l of incoming nitrogen was removed in the waste activated sludge. Hence the high nitrogen removal is the result of nitrification-denitrification with sludge wasting accounting for only 16% of the N removal as a result of the low observed cell yields encountered in high SRT processes.

The laboratory kinetic studies were shown to provide an accurate indication of what was occurring in the actual process. In all cases the nitrification kinetic rates were independent of exogenous NH_4^+-N concentrations down to $\lesssim$ 1 mg/l. The saturation constant for Nitrosomonas has been reported (8) to be in the range of 0.1 to 1.0 mg/l depending on the person conducting the study and the experimental conditions. If the growth rate is assumed to follow the expression $\mu = \mu_{max} S/(K_s + S)$, the growth rate would be 91% of the maximum value with an exogenous NH_4^+-N concentration of 1 mg/l and K_s of 0.1 mg/l. If K_s were as high as 1.0 mg/l, the growth rate would only be 50% of the maximum value at S = 1.0 mg/l. Obviously an accurate determination of K_s would require a concentrated effort to evaluate the biological response at low NH_4^+-N levels coupled with the use of an analytical procedure accurate at these low levels. Since this study did not include any attempt to estimate K_s and since the values reported in the literature vary by a factor of 10, there is no obvious reason for attempting to compare the observed system responses and laboratory kinetic data on the basis of Michaelis-Menten kinetics when using an undetermined saturation constant. Rather the simple application of linear rates to the initial two complete mix passes is sufficient to describe general process nitrification response as long as the residual NH_4^+-N concentration in the second pass is > 1.0 mg/l.

The denitrification rates occurring in the process (Tables 7 and 32) were also found to be comparable with the rates observed in the laboratory kinetic studies. Since the COD loading cycled throughout the day, the process denitrification rate should also vary during the day. For this reason, the denitrification rate calculated at a given point in time should not necessarily agree with a laboratory rate unless the aeration period and organic loading were comparable in each unit.

The laboratory studies of the type shown in Table 1 consistently indicated that there was no apparent advantage to a flow-splitting approach as long as the length of the aeration period was not substantially in excess of the time required to attain "complete" nitrification. The average 22% increase in the denitrification rate with supplemental primary addition was not sufficient, for the purposes of this study, to warrant increasing the effluent NO_3^--N levels. This increase in NO_3^--N would occur because the NH_4^+-N introduced into the denitrification section would be subsequently oxidized to NO_3^--N in the terminally aerated section of the reactor. This residual NO_3^-

could be eliminated in an additional nitrification-denitrification cycle, but there is no apparent advantage to this approach over the one utilized.

The nitrification and denitrification kinetic rates in Tables 1 and 5 summarize some of the more obvious advantages and disadvantages of the single nitrification-denitrification approach to nitrogen removal. For a wastewater such as that in Washington, D.C. with the temperature varying from around 15°C in the winter to around 26°C in the summer there will be an apparent 3-fold change in nitrification kinetic rates from winter to summer (Figure 27). There is also the probability in most design situations that one must deal with a diurnal flow/concentration cycle. If one has a modest 3:1 maximum:minimum flow variation synchronous with a 3:1 concentration change coupled with a long range 3:1 influence of temperature, then there is actually a 27-fold difference in the combination of aeration time and solids levels which are required during the year to provide the optimum conditions (aeration just sufficient for "complete" nitrification) in a perfect plug flow reactor. In many small plants a 6-7:1 maximum:minimum flow variation is not unusual and this could mean a 50-100 fold difference in producing optimum conditions in a perfect plug flow reactor during the course of a year. As shown in Table 5, the penalty for always providing sufficient aeration time/solids to meet the peak loading for a day is a reduction in the subsequent denitrification rates which will prevail under lower loading conditions. The lower rates will be offset by lower (NO_3^-)-N concentrations to be biologically reduced with the time available for dissimilation determined by the hydraulic flow characteristics of the plant. Obviously, the use of complete mix tanks and flow equalization can attenuate the impact of incoming flow/concentration changes considerably.

The single stage nitrification-denitrification process can clearly be operated to handle the concentration variations which occur during the day. This was demonstrated in the long period of operation of the process. Also, the results of the July 11-September 22 operation (Tables 11 and 12) show that the system can respond to moderate diurnal flow changes and still produce an effluent low in total N. The application of the laboratory kinetic rates to estimate the amount of N that could be oxidized in the first two passes was shown to produce results which agreed closely with the amount of $(NO_2^- + NO_3^-)$-N in the final effluent. Where insufficient aeration time was available in the initial aeration sequence to oxidize all of the incoming NH_4^+-N, there was a corresponding rise in the effluent $(NO_2^- + NO_3^-)$-N level reflecting oxidation of this material in the terminal aeration step.

The results obtained from the system during the period of $FeCl_3$ addition indicate that this metal salt can effectively remove the influent phosphorus with no impact on the nitrifying organisms. This has been shown by several other investigators so the result was expected. The $FeCl_3$ dosage was selected to maintain a pH of $\geq$ 6.5 in the terminal aerated chamber. At the rather moderate dosages utilized, the P removal for the entire 70-day period of $FeCl_3$ addition was 89% with most of the effluent P associated with particulate matter/biological solids. Filtration of the clarified effluent over the 43-day period of October 9-November 20 reduced the effluent P from 0.61 mg/l to 0.25 mg/l. The $FeCl_3$ addition resulted in the build-up of a large amount of chemical sludge with a reduction of the MLVSS to near 50% of the MLSS.

This necessitated carrying higher MLSS in the reactor to maintain the desired process loading. The settling velocities (Table 33) were about the same as encountered at similar temperatures with no $FeCl_3$. The $FeCl_3$ improved the mixed liquor settling velocities over what would be anticipated in a comparable biological system (equal MLSS) without $FeCl_3$ addition. On balance, the increased in MLSS needed to maintain a suitable SRT was largely compensated for by the increased settling velocities.

As shown in Tables 20 and 21, filtration of the clarified effluent produced a final effluent of excellent quality. The desirability of using the larger media can clearly be seen. Each of the filters produced an effluent of identical quality but the run lengths with filter "P" were substantially longer than when using filter "N." These results are consistent with previous observations made during an in-depth evaluation of these filter media (17).

The few brief studies summarized in the Appendix indicate that Cl_2 addition is potentially more useful than is H_2O_2 for controlling nuisance heterotrophic growths in systems where nitrification must be maintained. H_2O_2 dosages near the minimum values reported to be useful against filamentous forms (22) had a marked impact on nitrification. In contrast, moderate HOCl dosages to the recycle solids were not detrimental to nitrification. Obviously, the usefulness of Cl_2 in any given situation will depend on the resistance of the heterotrophic organisms causing the problems and the dosages and point of application (especially because of the potential for chloramine formation).

The results summarized in the previous section indicate that a single nitrification-denitrification approach in a "plug-flow" reactor is a reliable means of achieving nitrogen removal beyond that attributable to cellular synthesis. This approach is best suited to relatively uniform flows and NH_4^+-N concentrations but this is not a requirement of the system. Flow equalization or use of alternative approaches such as shown in Figure 1 can help overcome non-uniform loadings. Depending upon the discharge standards which have to be met, one could construct a multipass system such as used here with sufficient flexibility to vary the number of aerated passes. In winter operation the number of aerated passes could be sufficient to provide complete nitrification and whatever denitrification could be attained in the remaining stirred passes. In warm weather operation the increased nitrification kinetic rates and improved settling velocities make possible the use of a reduced number of aerated passes. Even where the discharge standards are more stringent than can be reliably achieved by single stage systems, the use of these systems should not be automatically precluded. If the system used in this study were combined with an additional staged denitrification sequence using methanol, for example, one could operate the first process in a way to insure complete nitrification at all times with some variation in available denitrification capacity and still obtain a substantial savings in the methanol requirement in the subsequent denitrification step.

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APPENDIX

As indicated in Section 5, a few laboratory studies were undertaken to assess the potential usefulness of H_2O_2 or HOCl for the control of heterotrophic nuisance growths without impairing the nitrifying organisms also present.

In the first study with H_2O_2, 500-ml of recycle solids from the single stage nitrification system were added to each of 5 beakers. H_2O_2 (Becco 35% obtained from FMC Corporation) was added to each beaker to yield the following concentrations: 0, 18.9, 37.7, 75.4 and 113 mg H_2O_2/1. The contents of each beaker were mixed and after 1-3 minutes, 1 liter of D.C. primary effluent was added to each system to yield final H_2O_2 concentrations of 0, 6.3, 12.6, 25.1 and 37.7 mg/1. This mode of peroxide addition simulated to some degree what would occur if the H_2O_2 was added to the recycle line of an actual process. Each of the beakers was aerated after the primary effluent was added, and samples were withdrawn periodically for $(NO_2^- + NO_3^-)$-N analysis. Results are presented in Figure A-1. No affect was observed at the lowest dosage. However, initial dosages of 37.7 and 75.4 mg H_2O_2/1 produced rates which were only 53% and 18% of the control respectively. Hence nitrification was severely reduced at a final simulated concentration in a reactor (recycle plus primary) of 25 mg/1.

In an attempt to more closely define the inhibitory dosage and to eliminate the possible effect of an initially high concentration of H_2O_2, an additional series of studies was undertaken in which the peroxide was added to a mixture of recycle and primary effluent simulating addition directly to the mixed liquor of a process. Results are presented in Figure A-2. The peroxide began to inhibit nitrification at a dosage between 10 and 20 mg/1, and a 64% inhibition was observed at 40 mg/1. The results reported by Cole, et al. (22) indicated that a minimum dosage for filamentous organism control presumably lies between 10 and 40 mg H_2O_2/1. Better results for many filamentous forms were obtained with dosages of 100-250 mg/1. The laboratory studies, therefore, indicate that there would be little chance of filamentous control by H_2O_2 without the concurrent elimination or severe inhibition of nitrification. If peroxide were tried in an actual process, close control of the dosage would be required.

Since these two studies indicated that H_2O_2 had little potential for controlling the filamentous organisms frequently encountered with activated sludge systems treating D.C. wastewater, the remaining studies were focused on the potential of chlorine. In all cases Clorox was used, and the equivalent Cl_2 dosage was determined by the procedure in Standard Methods (10).

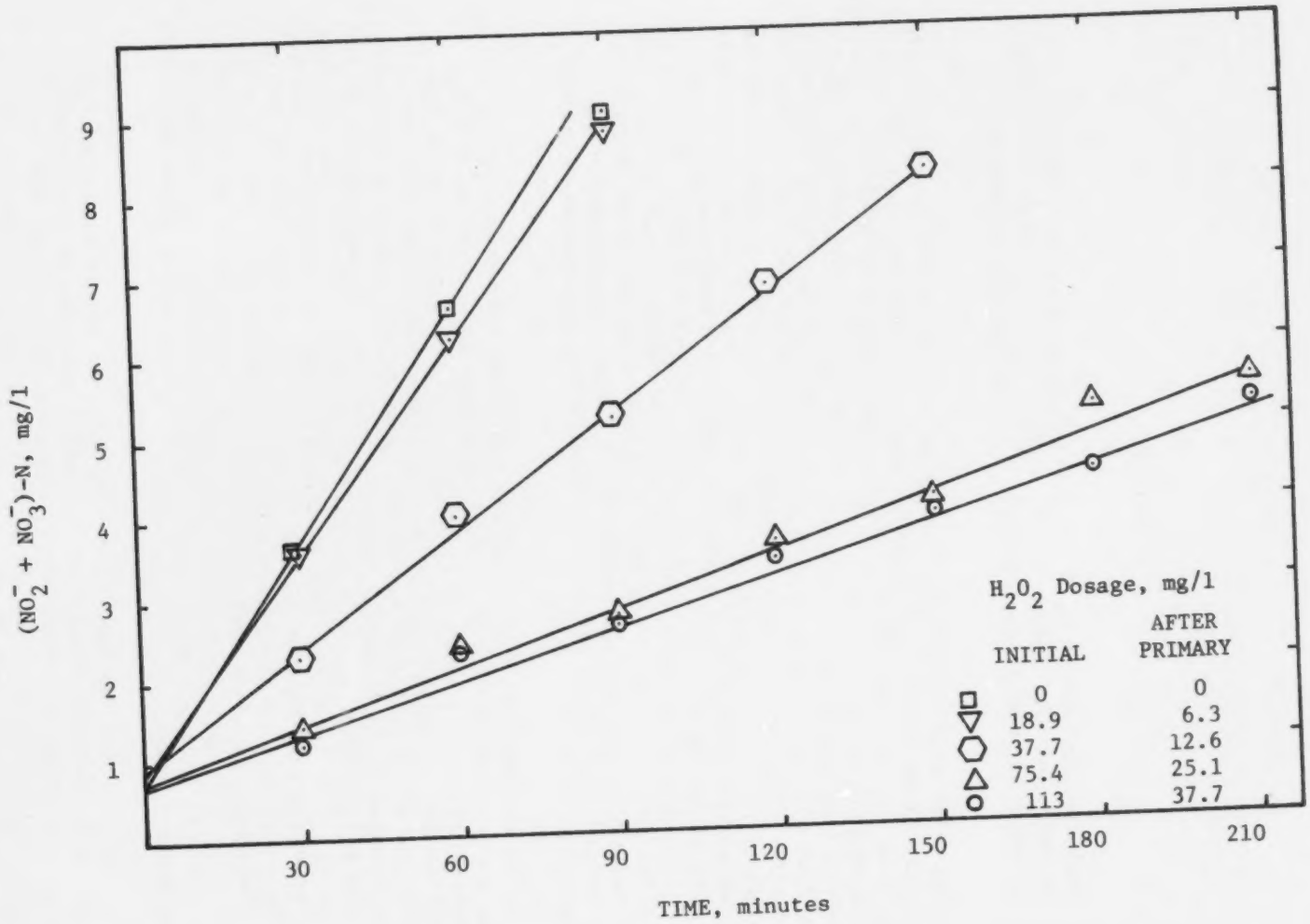

Figure A-1. Effect of H_2O_2 dosage on rate of nitrification in first laboratory test.

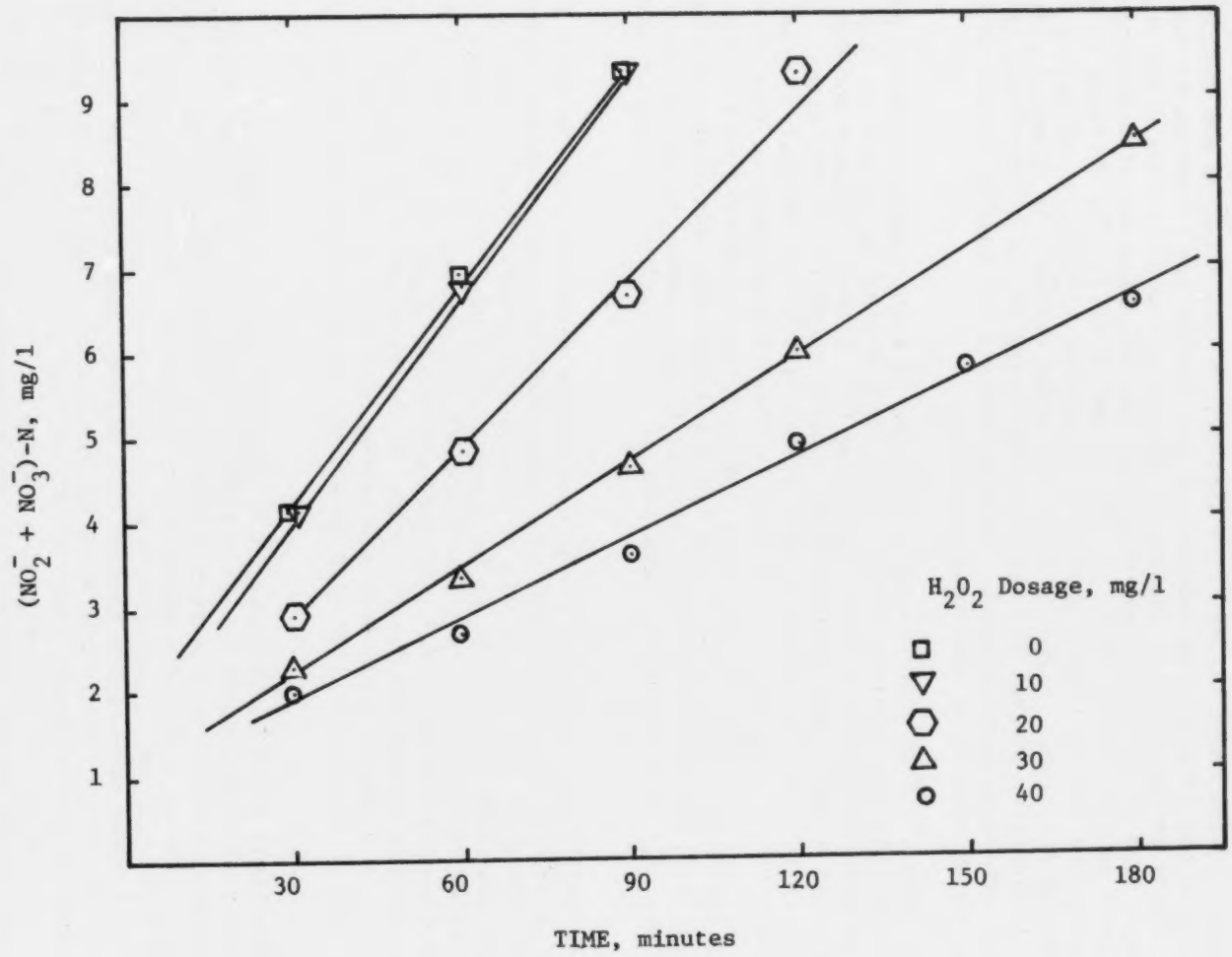

Figure A-2. Effect of H_2O_2 dosage on rate of nitrification in second laboratory test.

Clorox (equivalent Cl_2 = 112 mg Cl_2/ml) was added to five samples of recycle from the single stage system at equivalent Cl_2 doses of 0, 1, 2, 4 and 8 mg/l. The recycle samples were stirred for several seconds and then primary effluent was added in a 2:1 ratio to produce final equivalent Cl_2 doses of 1/3 the above values. The increase in $(NO_2^- + NO_3^-)$-N was monitored in each of the five aerated samples and the results are presented in Figure A-3. There was no apparent inhibitory affect on the nitrifying organisms. The same type of experiment was conducted the following day with equivalent Cl_2 doses to the recycle of 0, 10, 20, 30 and 40 mg/l. The decrease in NH_4^+-N was monitored and once again there was no apparent inhibitory affect on the nitrifying organisms. Based on these two brief studies, it appeared that one could potentially control filamentous growth with Cl_2 in a nitrifying system without affecting nitrification. This hypothesis was further tested on a larger scale with three additional studies.

A 28.9 m^3 (7630 gal) reactor consisting of eight completely mixed passes in series (16) was operated at the pilot plant during the summer of 1975. This activated sludge system was receiving D.C. primary effluent and was operated at a sufficiently high SRT to achieve complete nitrification. Clorox was fed to the recycle stream of this system at a point immediately prior to its entering the reactor for a 19-hour period. The steady feed rate of 13.5 ml/min (86 mg Cl_2/ml equivalent strength) corresponded to a Cl_2 dosage of 8.8 mg/l based on the steady 132 l/min (35 gpm) influent flow. As shown in Table A-1, the system continued to nitrify throughout the period of Clorox addition. The data suggests a reduction in the nitrification rate of about 20%.

An additional study was conducted with the 8-pass reactor in March 1976 using an applied Cl_2 dosage near the upper limit of values commonly reported in the literature for the control of filamentous growth. Clorox (106 mg Cl_2/ml) was added for 19.5 hours at a steady rate of 21.4 ml/min. which resulted in an equivalent chlorine dosage to the process of 20.3 mg/l based on the steady 112 l/min (29.5 gpm) influent flow. Again the Clorox was added to the recycle stream immediately prior to the point where it entered the reactor. As shown in Table A-2, the system continued to nitrify throughout the period of Clorox addition with no obvious impact on the nitrification rate.

The final pilot plant study to be reported was conducted with a completely mixed activated sludge system operating on D.C. primary effluent. The system was operated at a steady flow of 114 l/min (30 gpm) for a reactor detention time of 4.31 hours based on influent flow. The recycle flow rate was 49 l/min (13 gpm). Clorox with an equivalent Cl_2 concentration of 111 mg Cl_2/ml was added at a steady flow of 10.9 ml/min. The Clorox was added to the recycle stream immediately ahead of the reactor. Based on the average 114 l/min (30 gpm) influent flow, the Clorox addition corresponded to a Cl_2 dosage of 10.6 mg/l. The dosage was started at 1300 hours on March 15 and continued for 24 hours. Reactor D.O. was maintained above 3 mg/l. The reactor solids concentrations and $(NO_2^- + NO_3^-)$-N concentrations are summarized in Figure A-4. The reactor NH_4^+-N concentration remained below 1 mg/l throughout the period of Clorox addition and for the additional day that monitoring was continued.

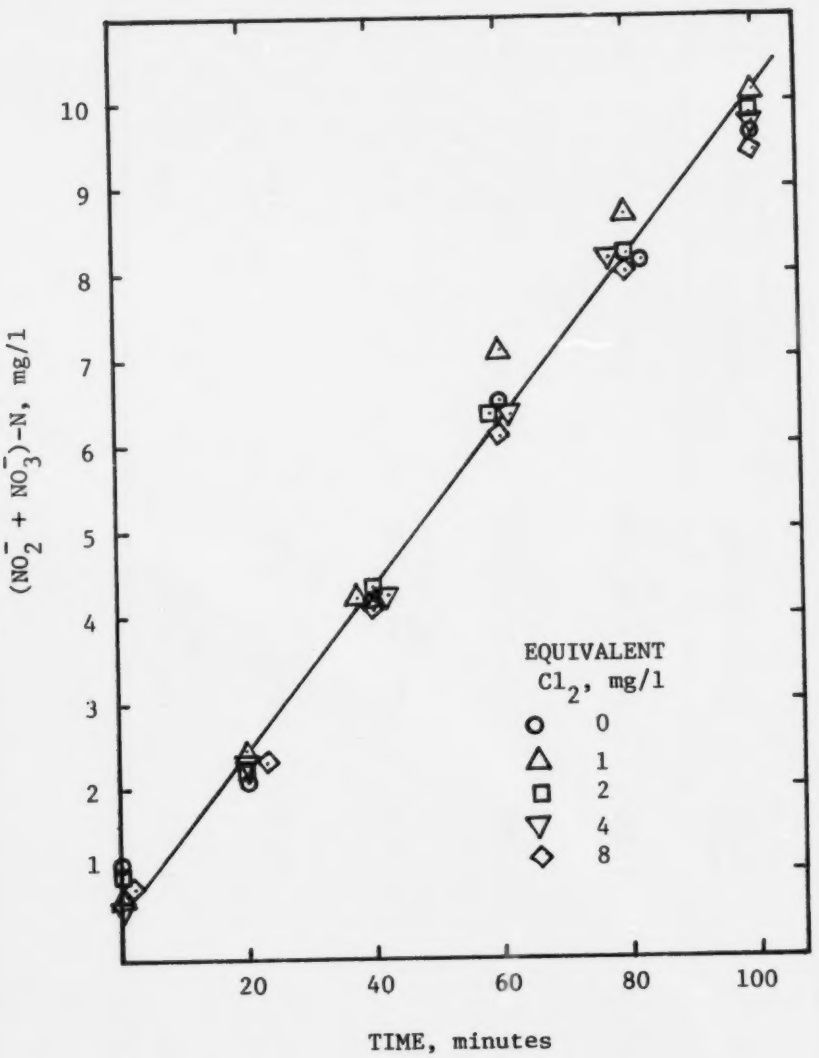

Figure A-3. Effect of Clorox addition on rate of nitrification.

TABLE A-1. NH_4^+-N AND (NO_2^- + NO_3^-)-N LEVELS IN A SIMULATED PLUG FLOW SYSTEM DURING CLOROX ADDITION (SEPTEMBER 17-18, 1975)*

Date	Time	MLVSS mg/l	Parameter	Concentration, mg/l Pass 1	Pass 2	Pass 3	Pass 4
9/17	1330	1,250	NH_4^+-N				< 1.0
			(NO_2^- + NO_3^-)-N	4.3	6.9	9.1	10.9
9/17	1520	1,260	NH_4^+-N				2.7
			(NO_2^- + NO_3^-)-N	4.6	7.5	9.1	11.5
9/17	2100	1,070	NH_4^+-N				7.1
			(NO_2^- + NO_3^-)-N		4.7		7.5
9/18	0100	1,260	NH_4^+-N				3.2
			(NO_2^- + NO_3^-)-N		5.6		9.2
9/18	1000	1,240	NH_4^+-N				1.3
			(NO_2^- + NO_3^-)-N		5.3		8.6

* Clorox Addition Started on 9/17 at 1400 hours
* Clorox Addition Ended on 9/18 at 0850 hours
* Influent Flow = 132 l/min (35.0 gpm)
* Temperature = 25°C
* Recycle Flow = 42.4 l/min (11.2 gpm)

TABLE A-2. NH_4^+-N AND (NO_2^- + NO_3^-)-N LEVELS IN A SIMULATED PLUG FLOW SYSTEM DURING CLOROX ADDITION * (MARCH 24-25, 1976)

Date/Time	NH_4^+-N, mg/l	(NO_2^- + NO_3^-)-N, mg/l			
	Pass 6	Pass 2	Pass 4	Pass 6	Pass 8
3/24					
1100	< 0.2	5.1	7.8	7.7	8.0
1500	< 0.2	6.0	11.2	11.8	11.5
2000	< 0.2	6.4	11.8	13.1	13.7
3/25					
0200	0.4	5.1	10.1	11.1	11.4
0800	0.8	6.0	8.6	9.1	9.5
1300	< 0.2	6.7	9.3	9.3	8.8

*Influent Flow = 112 1/min (29.5 gpm)
*Recycle Flow = 60 1/min (15.9 gpm)
*Temperature = 18°C
*Clorox Addition Started @ 1100 hours on 3/24
*Clorox Addition Ended @ 0630 hours on 3/25

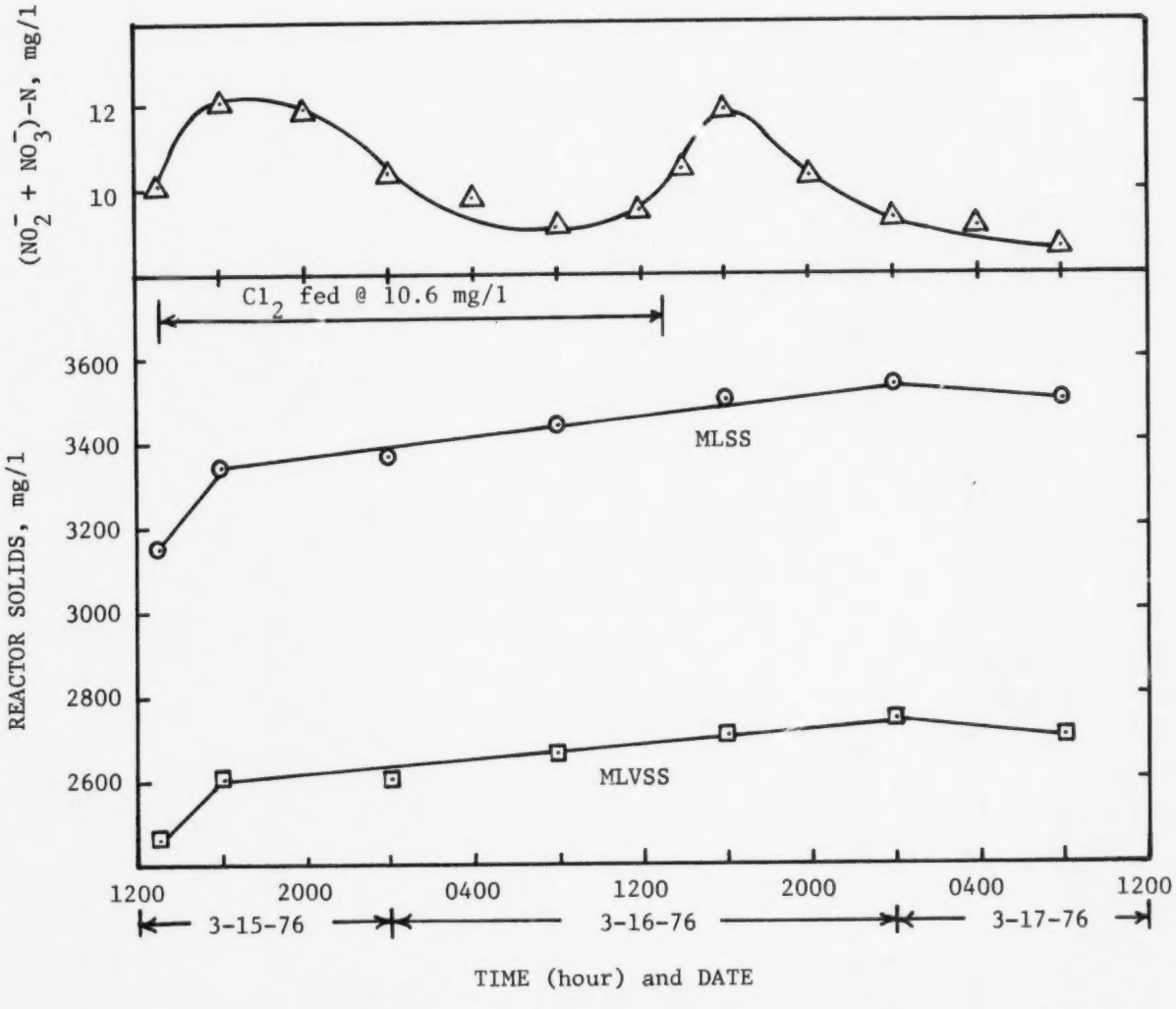

Figure A-4. Reactor solids and $(NO_2^- + NO_3^-)$-N levels in a complete mix reactor during and after Clorox addition.

These brief studies indicated that chlorine dosages in the range commonly utilized for the control of many nuisance filamentous forms can be applied without any drastic impact on the nitrifying organisms. The effect of continuous chlorine addition over long time periods was not examined, and hence the Cl_2 dosages successfully used here may not be feasible for extended operation. However, continous Cl_2 addition at low dosages was stated to be effective for control of sludge bulking at the Central Contra Costa plant without impairing nitrification efficiency (1).